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CHARLES D. WALCOTT,
Secretary of the Smithsonian Institution.

CONTENTS

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The Present Distribution of the Onychophora, a Group of Terrestrial Invertebrates

BY
AUSTIN H. CLARK

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THE PRESENT DISTRIBUTION OF THE ONYCHOPHORA, A GROUP OF TERRESTRIAL INVERTEBRATES.

By AUSTIN H. CLARK

CONTENTS

PREFACE

A close study of the geographical distribution of almost any class of animals emphasizes certain features which are obscured, or sometimes entirely masked, in the geographical distribution of other types, and it is therefore essential, if we would lay a firm foundation for zoögeographical generalizations, that the details of the distribution of all types should be carefully examined.

Not only do the different classes of animals vary in the details of their relationships to the present land masses and their subdivisions, but great diversity is often found between families of the same order, and even between genera of the same family. Particularly is this true of nocturnal as contrasted with related diurnal types.

As a group the onychophores have been strangely neglected by zoölogists. Owing to their retiring habits they are difficult to find, and few collectors have devoted their attention particularly to them. Thus the majority of the species are known from very few specimens, which often were collected more or less accidentally. For instance the original examples upon which the Rev. Lansdown Guilding based the name *Peripatus juliformis,* creating for the new form the class Polypoda in the phylum Mollusca, were collected by him in St. Vincent in 1825; only once since have specimens of this species been

found—by Mr. H. H. Smith in 1894—though many naturalists, myself among the number, have searched for them.

It is of course impossible to approach a discussion of the distribution of the onychophores in the same way in which one would approach a discussion of the distribution of better known types, for the number of genera and species yet remaining to be discovered is undoubtedly large in proportion to the number of the genera and species which have already been described, while we do not know with any degree of accuracy the range of even a single form.

In many of the zoögeographically most important regions of the world no onychophores have as yet been found, though in some of them they certainly exist. Unidentified species, which were not preserved, have been met with in the Philippines and in Fiji, but none have been reported from New Caledonia, Samoa, the Solomon Islands, Halmahera, Celebes, Borneo, the Sunda Islands east of Sumatra, or Madagascar, where almost certainly they occur, or in southeastern Asia outside of the Malay Peninsula, though there should be representatives of the group in Ceylon and southern India as well as in Burma and Siam and the adjacent lands. Excepting for those in the Cape Colony and Natal we know practically nothing of the African types.

A discussion of the distribution of the onychophores therefore must take the form of a simple exposition of the generally accepted facts in zoögeography and palæogeography, and an exposition of the evidence for or against these facts presented by the species of the group as we know them now.

THE ONYCHOPHORES APPARENTLY AN ANCIENT TYPE

Although we have no palæontological evidence upon which to base our statement, it would appear that the onychophores represent a very ancient type for, like most ancient types, (1) they are strictly nocturnal, (2) they are all built upon the same plan with very little deviation from the mean, and (3) they indicate land connections which we know to have been very ancient.

THE PHYSICAL AND ECOLOGICAL DISTRIBUTION OF THE ONYCHOPHORES

So far as we know, the onychophores are confined within a relatively narrow and circumscribed physical range; that is, they require a fairly uniform temperature within very moderate extremes, and a uniformly high humidity.

This means that many barriers have operated as a check to their dispersal which are readily passed by the great majority of the other terrestrial types, both invertebrate and vertebrate, and suggests that the facts presented by the distribution of the onychophores possesses exceptional value.

Although existing within very narrow physical limits, the onychophores are in certain ways more independent of their immediate surroundings than the great majority of invertebrates, for they are predacious, and apparently feed upon any organisms small enough for them to overcome. This renders them quite independent of the distribution of the plant species, which determines the distribution of many insects, and which in turn is governed to a large extent by the underlying geology of the regions in which the plants occur.

THE THERMAL DISTRIBUTION OF THE ONYCHOPHORES

The mean annual temperature of the portions of the world inhabited by the onychophores varies from 50° to 80° F. (10.00° to 26.67° C.), though certain forms occur locally in average temperatures slightly in excess of both of the extremes given. So far as we are able to calculate from the estimated temperatures of their habitats, most of the species occur between the limits of 60° and 70° F. (15.56° and 21.11° C.), which appears to be the optimum temperature range for the group, suggesting that it was between these temperatures that these animals originated.

A critical study of the recent crinoids shows that their optimum temperature is between 55° and 65° F. (12.78° and 18.33° C.), and I have suggested that it was probably within this temperature range that the post-palæozoic crinoid fauna, at least, attained its greatest development.[1]

Combining the data deduced from the study of these two groups, the one marine, the other terrestrial, we find a coincidence of the optimum conditions for both between 60° and 65° F. (15.56° and 18.33° C.).

GENERAL FEATURES OF THE DISTRIBUTION OF THE ONYCHOPHORES

The most striking feature of the geographical distribution of the onychophores as we know it today is the restriction of all the species

[1] Une étude philosophique de la relation entre les crinoïdes actuels et la température de leur habitat. Bulletin de l'Institut Océanographique (Fondation Albert I[er], Prince de Monaco), No. 294, 20 Juin, 1914.

to the region south of the Tropic of Cancer, and of the great majority of them to the southern hemisphere; only in the West Indies and in Central America do we find an appreciable number north of the equator.

Another very striking feature is the geographical distinctness of the systematic units. Nowhere, so far as we know, do species of the Peripatidæ and of the Peripatopsidæ occur together. The two subfamilies of the Peripatidæ are separated by the entire breadth of the Indian Ocean.

In the subfamily Peripatinæ, *Mesoperipatus* is separated from *Oroperipatus, Macroperipatus, Epiperipatus, Plicatoperipatus* and *Peripatus* by the expanse of the Atlantic Ocean; *Plicatoperipatus* is isolated on the island of Jamaica where, however, *Peripatus* is also found; *Oroperipatus* occurs almost exclusively west of the watershed between the Pacific and the Atlantic in Central and South America; *Peripatus,* however, also occurs within its territory; *Macroperipatus* and *Epiperipatus,* both generally distributed over tropical America east of the Andes, occur over practically the same area, though the former is absent from Tobago and Grenada where the latter occurs; *Peripatus* is found with them over a small area in northern Venezuela. *Peripatus* alone occurs in the Antilles, except on Jamaica, where *Plicatoperipatus* also is found, and on Cuba, Grenada, Tobago and Trinidad, from which islands it is absent.

The two subfamilies of the Peripatopsidæ are entirely separate in the Australian region, one (Peripatopsinæ) being confined to New Guinea and the adjacent islands, the other (Peripatoidinæ) occurring in Australia, Tasmania and New Zealand, though both exist together in South Africa; in each subfamily the genera found in South Africa represent a systematic type markedly different from that found further to the east. The subfamily Peripatoidinæ is represented in Chile.

We are thus able to recognize among the onychophores traces of a zonal distribution such as is suggested by many other types, best marked in the east, the Peripatidæ being equatorial (the Malay Peninsula and Sumatra, central Africa and tropical South and Central America), the Peripatopsinæ intermediate (New Britain, New Guinea and Ceram, Natal, and the adjacent portions of Cape Colony), and the Peripatoidinæ austral (Australia, Tasmania and New Zealand, Natal and the Cape Colony, and Chile).

THE DISTRIBUTION OF THE PERIPATIDÆ

The distribution of the species of Peripatidæ indicates that, so far as the onychophores are concerned, Sumatra and the Malay Peninsula, central Africa and tropical America collectively form a zoögeographical unit.

This agrees with what we conclude from the distribution of other types, most of which, however, fall into two groups, an Afro-American and an Afro-Malayan.

No onychophores have as yet been reported from southern India. On the basis of what we know of other forms we would expect in this region a genus or genera more closely related to African than to Malayan types.

Of the genera inhabiting the zoögeographic area under consideration *Eoperipatus* (belonging to the subfamily Eoperipatinæ) of Sumatra and the Malay Peninsula shows the highest degree of specialization, and is rather abruptly differentiated from the remaining three genera, which collectively form a distinct systematic unit (the Peripatinæ).

Mesoperipatus of central Africa is considerably less specialized than *Eoperipatus,* though more specialized than *Peripatus* of eastern South and Central America, which in its turn is more specialized than the very primitive and worm-like *Oroperipatus* of South and Central America west of the crest of the Andes.

EXPLANATION OF THE DISTRIBUTION OF THE PERIPATIDÆ

In order that the facts brought out by the geographical distribution of the genera and species of the Peripatidæ may be understood, it is necessary first to give a brief sketch of the processes by which the geographical differentiation of animals is brought about.

The physical and economic conditions under which any new animal type arises are naturally the optimum conditions for the perpetuation of that type in its original form, and the generative center, or the center of distribution, of the type will be the locality where the optimum conditions represent the average or mean of a long range of imperceptibly varying conditions, representing all of the conditions under which it is possible for the type to exist, and therefore permitting of progressive deviation from the original type through gradual adaptation for a maximum distance in a maximum number of directions.

Any animal type once evolved will extend itself immediately in every direction as far as the natural barriers to its further dispersal

will permit; but in proportion as it departs from the region where the optimum conditions represent the mean of a wide range of conditions, it will become less and less capable of producing subtypes, for not only is the range of conditions under which it is capable of existing constantly narrowing, at the natural barriers becoming reduced to the vanishing point, but also the time taken in its migration represents so much time lost from its virile and adaptable type youth, and a corresponding advance toward a more or less inert and inflexible type maturity.

On the borders of the range of any type, where the range of the conditions under which it is possible for it to exist is very small, there will be found a great number of localities where the type is able to maintain itself, each of these localities differing slightly from all the others, thermally or economically, or otherwise. Such thermal or economic differentiation is of course also geographical. There will thus result a large number of allied forms which, however, cover collectively a small economic and physical range.

An animal type intruding into a new and favorable area will at once, through the opportunities of existence offered its less efficient individuals, tend toward an excess of individual variation, which may become extreme, until through the pressure of its own increasing numbers, and the constantly increasing severity of its internal competition, it begins to weed out the numerous less efficient varieties, and to narrow them down to a very few, or even to one only, which exist each within very restricted structural limits.

Thus the existence in any area of a great number of closely allied forms indicates either (1) the existence of a very restricted physical or ecological range in which the type can maintain an existence, in which case the corresponding organic varieties will be evidenced as geographical forms (in the strictest sense of the term), or (2) a region newly colonized, in which case a large number of more or less closely related types will be found intermingled, or but partially localized.

The migratory birds offer, in the light of the preceding statements, an instructive study in primary and secondary colonization.

In the summer the temperate regions of the northern hemisphere (and to a much less extent the southern) support many bird types which are divided into a large number of local races, each local race being a direct adaptation to a local enviroment which represents economically or physically a very narrow ecological range, the sum total of these narrow ecological ranges being the total range under

which the type as a whole can maintain itself, a total range which is always duplicated within the tropics.

Bird types which exist only in a great number of local forms cannot be assumed to be living under optimum conditions for the type as a whole. Such bird types, living always within tropical conditions, are probably all of ultimately tropical origin, their progenitors having gradually extended their range outward from the tropics with the annual outward extension of the tropical conditions, and eventually having colonized, though in the summer only, the temperate regions.

To a type with a highly developed power of migration, such as many birds, the temperate regions in the summer represent the border of a tropical habitat, and thus we should expect to find such a type occurring in the temperate regions in summer obeying the laws of peripheral distribution of animal types in general.

In the winter these migratory birds, in order to remain within the economic range necessary for their existence, of necessity withdraw within the tropics (where, as non-breeders, they are perfectly well able to exist) there to remain until, with the advent of summer, the tropical conditions are again extended.

But in the tropics the sum total of the range of each type is duplicated, and conditions are such that there is no closely circumscribed local and ecological differentiation comparable to that which occurs in the temperate regions.

Therefore there is no compelling reason for the various races to maintain their summer segregation, and a number of these races may be found living together.

Many of these bird types have breeding representatives in the tropics, especially on isolated islands where the factors which, after the summer colonization of the temperate regions, caused their extirpation as breeding residents from their original tropical home, have not operated; the non-breeding individuals of many others appear to prefer always to remain within the tropics.

These bird types within the tropics are secondary colonists, returned to their original area of optimum conditions, where they are able to exist as adults in a great number of closely related forms, but where nidification, unless of a newly acquired highly specialized type, or in especially protected localities, has now, thanks to the development of certain enemies, become impossible.

In any area in which the optimum conditions for a given animal type are represented by the mean of the conditions under which that type is able to maintain itself, the progressive development of that

type, after its first appearance, whether by original generation or introduction from outside, will (as in part suggested by the behavior of introduced species) be marked first by individual variation, soon leading to more or less fixed varieties, and finally to the evolution of new species and even new genera, each of which was originally the exponent of conditions more or less different from those under which the type originally appeared.

Now in most large genera we find among the component species one which in its characters occupies the mean between the extremes shown by the other forms, and which typically covers the entire economic, physical, and geographical range of the genus, unless the species on the borders of the generic range are isolated by barriers.

Obviously this is the species best adapted to the conditions of the present day and, if conditions should remain indefinitely as they are now, such a species would gradually succeed, by the mere force of numbers and greater procreative power, which have already enabled it to overrun all the other forms, in exterminating all of the other species of the genus which it was able to reach.

As families and orders are constructively the same as genera, we typically find in them a highly dominant genus, subfamily, or family, which stands in the same relation to them that the dominant species does to the genus.

And among the higher groups the same thing is repeated; thus, for example, we find among the mammals the rodents, among the birds the finches, among the fishes the perches, among the flies the muscoid types, etc., each group including species almost all of which are of small average size, yet never excessively small, representing the dominant types which appear to be on the road to supplanting all the other types through a development from their immediate stock of virile competing forms, and which, were conditions to remain indefinitely as they are at the present epoch, would eventually come to form the entire world fauna.

An appreciation of the normal existence of such a dominant type in each large and widely distributed group is essential for the comprehension of the fact that, given a number of closely related genera occupying a large area, but separated from each other by barriers, the genus occupying the center of distribution will be the most specialized, while that at the periphery will be the least specialized.

Let us suppose a genus recently arisen, occurring uniformly over a very wide area in the center of which the conditions grade very slowly from the optimum to impassible physico-economic barriers in each direction, while at the periphery the conditions grade very

rapidly from those capable of supporting the type to impassible physico-economic barriers.

It is evident that the individuals at the periphery of the area of distribution, living within a very narrow physico-economic radius, would have to restrict themselves within a very small structural compass, while those at the center of the area of distribution, existing in a very wide economic and physical radius, could wander very far away from the optimum structural condition without meeting prohibitive obstacles.

At the periphery of the range the physico-economic belt capable of supporting the type is so narrow that it serves only as the habitat of a single type, a type which will therefore maintain itself near the original type of the organism. Here additional types cannot arise in any one locality, though slightly different types will be found in adjacent localities each one of which differs slightly in its physical and economic characters from the others, but all of which are included within the narrow mean.

At the center of the area of distribution the physico-economic belt is very broad, and it grades imperceptibly away from the mean in either direction. Thus here the original type, instead of being preserved intact as at the periphery, will eventually be supplanted by a type of subsequent origin, and this latter type will be the one which of all the derivative types is capable of covering the maximum number of economic units.

The appearance of such a type, which is represented by the dominant type seen in each genus, family, and higher group, is inevitable; for the original type, occupying the mean of the conditions at the center of distribution, will gradually colonize all possible conditions departing from the mean in every direction, this being rendered easy by the very gradual changes from the optimum, and the very wide separation of the impassible physico-economic barriers. The colonists will be more or less modified to suit their new surroundings and, if the physico-economic belt be broad enough, will divide themselves into new types and subtypes. Eventually a type is certain to appear which will alone be capable of occupying all of the regions occupied by the organism as a whole, and which therefore will gradually supplant and finally exterminate all the other types; and this type will not be a primitive type, such as that which is maintained intact at the periphery of the area of distribution, but a much more specialized type; for though the mean of the conditions which it covers is the same as the physico-economic range in which the peripheral types

live, it is economically much more specialized in its inherent ability to exist over a very wide range. Though much more specialized than the original type, this new dominant type will also be much less specialized than many of the types which it supplants, which will have possessed a very high degree of specialization in order to meet very highly specialized conditions.

The sum of the effect of this organic progress may be expressed by the statement that any animal type, once evolved, will extend itself immediately in every direction as far as the natural barriers to its dispersal; a more specialized form (a dominant type) of the same animal, better fitted for the conditions under which it lives, will sooner or later be evolved somewhere in the central, or most favorable, portion of the territory inhabited by the original type; this new type will at once extend itself as did the original type; but in the meantime there may have arisen certain barriers which the second type cannot cross and beyond which, therefore, the first type is secure. Up to these barriers—high mountains, deserts, newly formed arms of the sea, or whatever they may be—the second type will gradually supplant the first, as a result of its better economic equipment and more perfect physical resistence, and the advantages which this better equipment and resistence give it in the struggle for existence. Thus we shall eventually find a specialized type beyond the limits of which occurs a more generalized type of the same organism. The subsequent evolution of additional types, which will most frequently occur at or near the so-called center of distribution as a natural result of the greater facility for adaptation due to the greater distance apart of the physico-economic barriers and the consequently greater radius of each type, will result in the gradual formation of a dispersal figure which would be ideally represented by a series of concentric circles, each of the circles representing a barrier, the small central circle enclosing the most perfected type and the peripheral band the most generalized, the intervening areas including intermediate types increasing in specialization toward the center.

The distribution of the Peripatidæ represents a sector of such an ideal dispersal figure; the center of distribution for the family is the Malayan region, where the most specialized type occurs; just west of this is the great barrier of the Indian Ocean; in central Africa we find a less specialized type which probably reached its present habitat long before the type now occurring in the Malayan region was evolved, and which has been protected from the encroachment of that type by the submergence of the land over which it originally migrated.

In the case of the onychophores the assumption that the Malayan region is the center of distribution is somewhat arbitrary, though the correctness of this supposition is strongly indicated by the fact that the phylogenetic lines converge there. Under the very nearly uniform conditions which prevailed in the distant past there was no such thing as a center of distribution; new forms arose anywhere, and immediately spread everywhere; but as the surface of the earth became differentiated into warm and cold regions and the mountain ranges attained progressively to greater and greater heights, it happened that, speaking broadly, the Malayan region as a whole remained the region of least diurnal and seasonal variability, and of the most delicately graded temperature differences, and therefore, as the region of the most nearly permanent conditions and of the most gradual differentiation in its physical and economic features, the region of maximum physical and economic radius, and of least interrupted progressive phylogenetical advance.

Among the other groups of terrestrial organisms there are few, if any, for which the Malayan region represents the sole center of distribution as it may almost be said to do in the case of the onychophores. Though in most cases, broadly speaking, the Malayan region may reasonably be regarded as the chief, and possibly ultimate, center of distribution, there are commonly additional centers of distribution each of which partakes more or less of the character of the primary Malayan center.

As has already been explained, it is characteristic of types which have newly entered upon very favorable territory to vary very greatly, and eventually to give rise to a large number of local forms, which, if not subjected to the competition of more efficient intruders, may be supposed, under fixed conditions, to persist for a very considerable length of time, and which will be diversified in direct proportion to the breadth of the physical and economic radius of the area. Such specific abundance therefore indicates not the center of distribution for any given type, but the periphery. Thus the great number of species in the genus *Oroperipatus* occurring west of the crest of the Andes indicates that this region, a region of small physical and economic radius, represents the extreme western limit, and the maximum distance from the generative center, of the area inhabited by the Peripatidæ, while similar conditions in the genus *Peripatus* indicate that their territory is only slightly less far removed from that center.

The explanation of the distribution of the species of the family Peripatidæ, viewed in the light of what we know in regard to the distribution of other animal types, appears to be as follows:

Occurring originally as a uniform or slightly varying organism over a land including the Malayan region (but not the Australian), central Africa, and northern South and Central America, the original prototype of the family became differentiated, taking on the aspect in which we see it today, by the following processes:

The increasing height of the Andes, besides enabling the species living in that region to maintain themselves in the most suitable temperatures, isolated at a very early epoch such individuals as were living west of their crest, rendering them secure from invasion by types of later origin economically more specialized, and fitted to occupy a habitat with a slightly higher average temperature.

A new type, an immigrant from the east, better equipped economically than the original type and with a slightly higher optimum temperature, reached Africa, northern South and Central America, overrunning and extirpating the original type from all the territory east of the crest of the Andes and later in a few places even invading the mountainous region itself. This type subsequently became locally differentiated, through the same processes by which it itself was originally evolved, into five subtypes, the three newer, more specialized and more efficient, extirpating the original immigrant (their immediate ancestor) wherever they were able to reach it.

But before the differentiation of this type into subtypes, though subsequent to the extension of its range westward as far as the Cordillera, Africa became separated from the Malayan region and, at about the same time, also from South and Central America, this latter process involving the submergence, or disruption from other causes, of the Antillean region, resulting in the formation of the West India archipelago.

So far as we know at present no representative of the original immigrant type remains in Africa, though it is quite possible that some eventually will be found there. Its single known derivative in this region, *Mesoperipatus,* though very different, approaches the Malayan type more closely than do any of the American types.

This may be due to either of two causes; southern India and Ceylon maintained a connection with Africa after their separation from the Malayan region, and it is possible that this more efficient type reached this region in or near its present form from the Malayan region just before the separation of the two, subsequently spreading to Africa, but being prevented from extending its range to America by the formation of the Atlantic Ocean; or, which is far more likely, these three types may be all of local development, the African approaching more

closely to the Malayan on account of a greater similarity of the conditions under which it was perfected.

In the Malayan region, subsequent to the separation from Africa, evolution gradually produced, through the processes which have already been given in detail, a more specialized type, *Eoperipatus,* which represents the dominant type under present conditions. It is possible that this represents the only type in the region, for it is the only type we know; but it is probable that subordinate types will eventually be discovered.[1]

THE DISTRIBUTION OF THE AMERICAN SPECIES OF THE PERIPATIDÆ

The details of the distribution of the American species of the Peripatidæ deserve special consideration. In South and Central America we find the very primitive *Oroperipatus* almost entirely confined to the territory west of the watershed of the Andes, only three species (*Oroperipatus bimbergi, O. multipodes* and *O. eiseni*) occurring in the mountainous regions east of the divide, while the remaining territory, including the West India islands, is occupied by the less primitive *Peripatus,* two species of which, in Colombia and Panamá, have gained a foothold in the area otherwise occupied solely by *Oroperipatus.*

While the species of *Oroperipatus* exhibit great uniformity, this is not by any means true of the species of *Peripatus,* which fall into four well marked subgenera; one of these subgenera (*Plicatoperipatus*) is, so far as we know, confined to the island of Jamaica; another (*Macroperipatus*) occurs from Rio de Janeiro northward to Vera Cruz, including the island of Trinidad; the third (*Epiperipatus*), with almost the same continental range, though not known either so far north or so far south, extends to Trinidad, Tobago, and Grenada; while the fourth (*Peripatus*), found in a small area between Caracas and La Guayra and Mérida in Venezuela, near Bogotá in Colombia, in northern Panamá, and in Costa Rica, is eminently characteristic of the Antillean region, being found on Jamaica, Haiti, and Puerto Rico, and on the Lesser Antilles from St. Thomas to and including St. Vincent.

It is worthy of especial mention that, whereas *Oroperipatus,* the most primitive type, is chiefly developed in, and very largely confined to, the cool regions of the high mountains, where very uniform

[1] Since this was written the related genus *Typhloperipatus* has been described from the adjacent portion of Tibet.

conditions of temperature and of humidity prevail, and *Peripatus* finds its optimum conditions in somewhat warmer regions, the two most specialized types, *Macroperipatus* and *Epiperipatus,* are chiefly characteristic of territory which is very warm, and more or less variable both in temperature and in humidity. In other words, increasing warmth of habitat is correlated with increased specialization of the organism, and increased differentiation into subtypes, suggesting that the original temperature under which the onychophores arose was more comparable to the average temperature of the habitat of the American genus occurring in the coolest situations than to that of the habitat of any of the others.

In the light of the preceding, and considered in connection with what we know of the distribution of other animal types, the explanation of the present distribution of this family in America appears to be as follows:

During the time tropical America was inhabited only by the primitive *Oroperipatus* type, before the intrusion of the *Peripatus* type from the east, the Cordillera had attained a height sufficient to prevent the intrusion into that region of the newer and more specialized forms originally developed under, and specialized for, an average temperature somewhat higher than the optimum for the primitive *Oroperipatus.*

This new intrusive type, economically more efficient than the type with which it came into competition, and better suited in every way to meet existing conditions, extirpated the latter as far westward as the crest of the Andes; and so complete was this extirpation that only three species of *Oroperipatus* are known to occur on the Atlantic side of the divide, *Oroperipatus bimbergi,* from Amagatal and Guaduas, Colombia; *Oroperipatus multipodes,* from Rio Amago, Colombia; and *Oroperipatus eiseni,* from the Rio Purus, Brazil, though undoubtedly many more will be discovered in the future. Indeed the intrusive type proved virile enough to enter the region west of the divide in Colombia, Panamá and Costa Rica, for we find *Peripatus* (*Peripatus*) *bouvieri* at Boca del Monte, near Bogotá, Colombia, and *Peripatus* (*Peripatus*) *ruber* at Rancho Redondo, Costa Rica, as well as at Lino, near Bouquete, in the Province of Chiriqui, Panamá.

At this epoch, when the Cordillera and the country to the west was inhabited by the *Oroperipatus* type, and the country to the east by the *Peripatus* type, South (and Central) America became separated from Africa by the formation of the Atlantic Ocean, the accompanying geological changes involving the disintegration of the Antillean region, through submergence or otherwise, into the West India

archipelago, exclusive, however, in the south, of Trinidad, Tobago and Grenada, which still remained united to the mainland.

These fundamental changes in the geological structure of tropical America induced corresponding alterations in the environment of all the terrestrial organisms, and it was possibly as a result of these alterations in environmental conditions that the two subgenera *Macroperipatus* and *Epiperipatus,* both more specialized and economically more efficient than the parent type, were given off from *Peripatus.*

The effect of the economically more efficient *Macroperipatus* and *Epiperipatus* upon the parent type, *Peripatus,* was the same as had been the effect of *Peripatus* upon *Oroperipatus; Peripatus* disappeared from every situation which they were able to reach.

Thus *Peripatus* disappeared almost completely from continental South and Central America, persisting only in the mountains of western Venezuela, Colombia, Panamá, and Costa Rica, from which territory we know the following species—*Peripatus* (*Peripatus*) *sedgwicki,* Caracas, San Esteban, La Moka, Las Trincheras, and La Guayra, Venezuela; *Peripatus* (*Peripatus*) *brölemanni,* Tovar, Raxto Casselo, and Puerto Cabello, Venezuela; *Peripatus* (*Peripatus*) *bouvieri,* Boca del Monte, near Bogotá, Colombia; and *Peripatus* (*Peripatus*) *ruber,* Rancho Redondo, Costa Rica, and Lino, near Bouquete, in the Province of Chiriqui, Panamá. But the very process which caused *Peripatus* to disappear almost completely from the mainland of South America resulted in making it the characteristic type in the Antilles from Jamaica and Haiti eastward and southward to and including St. Vincent, for, thanks to the water barrier, *Macroperipatus* and *Epiperipatus* were not able to reach these islands, though they could, and did, reach Trinidad, Tobago, and Grenada, which at this time were a part of the mainland.

It is possible that the origin of *Macroperipatus* was subsequent to that of *Epiperipatus,* so that it was prevented from reaching Tobago and Grenada by the separation of those islands from the mainland after the intrusion of *Epiperipatus.*

The subgenus *Plicatoperipatus* appears to be, so far as we are able to see at present, of local origin in the island of Jamaica; it is quite possible, however, that it occurs in Haiti also.

The occurrence of *Epiperipatus* upon Grenada, Tobago, and Trinidad, and of *Macroperipatus* upon Trinidad, the very close relationship between the species of *Epiperipatus* upon Tobago and Trinidad,[1] and

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[1] Piccole Note su degli Onychophora. Zool. Anzeiger, Bd. 42, Nr. 6, S. 253-255. 18 Juli 1913.

the absence of *Peripatus* from these islands, may be thus accounted for.

Grenada lies not upon the ridge supporting Trinidad and Tobago, but upon the ridge supporting St. Vincent, St. Lucia, and the islands beyond. There is no evidence that it ever was connected with Trinidad or with Tobago. Certain elements in the fauna of Grenada, such as *Epiperipatus* among the onychophores, and very many types among the other groups of organisms, recall the fauna of Tobago and Trinidad, and separate Grenada sharply from the islands to the north. I believe that the island of Grenada, including the Grenadines to the northward as far as Bequia, first became separated from St. Vincent by the formation of a deep channel between them, and at a considerably later epoch, after the fauna of Grenada had become further modified by additions direct from South America (and not by way of Trinidad and Tobago), it became separated from South America, to which it had been joined in the general region of Margarita Island.

The fauna of Barbados (including, so far as we know, no onychophores) is the fauna of an oceanic island purely, being composed entirely of representatives of the most widely ranging and most easily transported of the organisms of the adjacent islands. Barbados has been entirely submerged since it formed a part of the ancient Antillean land.

No onychophores have ever been found in Cuba, though they have been diligently sought for there by a number of competent naturalists. If any are ever discovered it will be interesting to see whether they will belong to the subgenus *Peripatus,* like those on the other islands, or to *Epiperipatus,* like those on Grenada and Tobago, or to both *Epiperipatus* and *Macroperipatus,* like those on Trinidad.

The uniformity of the onychophores throughout the West India archipelago, both in the Greater Antilles and in the Lesser, is of much interest in indicating the original and fundamental unity of the entire group of islands. They do not indicate a zoögeographical division into a Greater and a Lesser Antillean fauna for the reason that their genera are uniformly distributed both in South and Central America, so that the same faunal elements would enter either group of islands in the event of a continental connection.

The close faunal affinity between the Antilles and the mountain region of western Venezuela, Colombia, Panamá, and Costa Rica indicated by the species of the subgenus *Peripatus* is not a true faunal affinity. It merely shows that in the Antilles and in the mountain region *Peripatus* has in exactly the same way been protected by barriers which have prevented the intrusion of the more efficient com-

peting forms which everywhere else have succeeded in extirpating it, in one case by barriers of water, in the other by barriers of mountain ranges.

THE DISTRIBUTION OF THE PERIPATOPSIDÆ

The family Peripatopsidæ includes fewer, but far more diverse, types than the singularly homogeneous Peripatidæ. It ranges from New Britain, New Guinea, and Ceram (in the Moluccas) to Australia, Tasmania, and New Zealand, and thence to southeastern and southern Africa, and to Chile.

The subfamily Peripatopsinæ inhabits New Britain, New Guinea, and Ceram, and also Cape Colony and Natal. At first sight this distribution appears to be quite anomalous, but in reality it agrees perfectly with what we know of the distribution of a number of other organisms, confirming the evidence presented in other groups of a past land connection between the Moluccas, New Guinea, and New Britain, and southeastern Africa.

The Peripatopsinæ and the Eoperipatinæ are not at present known to occur together anywhere in the east, being separated by a line passing west of the Moluccas.

This line, which separates the Peripatidæ from the Peripatopsidæ as well as the Eoperipatinæ from the Peripatoidinæ, is the equivalent of the famous Wallace's line, for it separates the Australasian from the Indo-Malayan types.

Unfortunately we cannot as yet, on the basis of the onychophores, say what the exact location of this line is; we only know that the genus characteristic of New Britain and New Guinea (*Paraperipatus*) occurs also on Ceram, and therefore the line must pass somewhere to the westward of Ceram, between Ceram and Sumatra, where the easternmost representative of the Peripatidæ occurs.

The distribution both of the Peripatidæ and of the Peripatopsinæ confirms the presence in the distant past of a land mass extending from the Malayan region westward and southwestward to central and southern Africa; and it is reasonable to suppose that the same land mass, though possibly at different epochs, served for the migration of both types, one passing over the more northern portion, the other over the more southern. The Peripatidæ passed over Africa into America, but the more specialized Peripatopsinæ, possibly later arrivals, went no farther than Africa.

In the Peripatidæ the most specialized type is that in the Indo-Malayan region, but in the Peripatopsinæ we find the most specialized

types in South Africa and the least specialized types in New Britain, New Guinea, and Ceram. This would appear to indicate that the headquarters of the group was originally somewhere between New Guinea and South Africa, and that New Guinea and the adjacent islands became very early detached and separated by a water barrier so that the endemic onychophores were protected from the intrusion of later and more efficient types, exactly as were the species of the genus *Oroperipatus* west of the Andes. If this view is correct, Madagascar should support a more specialized type of this subfamily than either South Africa or New Guinea and the adjacent islands.

We do not know any onychophores from the Cape York peninsula in Australia; it is probable that such forms as occur there belong to the Peripatopsinæ, and are related to the forms in New Guinea and the adjacent islands.

The distribution of the subfamily Peripatoidinæ is very interesting; this subfamily occurs in New Zealand, Tasmania, southern and western Australia, South Africa, and southern South America.

The forms occurring in Australia, New Zealand, and Tasmania collectively make up a very closely knit faunal unit, indicating the fundamental faunal homogeneity of these areas; Tasmania, however, lacks the less specialized component of the fauna of Australia and New Zealand, a fact which may or may not be significant. It is most probable that this type will eventually be found there.

There are two possible explanations for this distribution; (1) the species of this subfamily may have been extirpated from all the more desirable localities by more efficient and more aggressive species of the other groups, or (2) the subfamily may have attained its present distribution through following a more southern route.

The first of these alternatives seems untenable, for if it were so we should expect to find species of Peripatoidinæ north as well as south of the species of the other groups, and also occurring in isolated situations, such as mountain tops, where the other species could not penetrate. But nothing of the kind occurs. Moreover the species of the Peripatoidinæ are very highly specialized, so much so that if they came into competition with the species of the other families they probably would, other things being equal, prove themselves dominant.

Therefore we must tentatively accept the second alternative, namely, that the Peripatoidinæ attained their present distribution through originally having been widely spread over a southern land which at one time or another included within its boundaries New Zealand, Tasmania and southern South America, as well as South

Africa. This hypothesis, moreover, accords with what we know of the distribution of many other southern types.

As the American species of Peripatoidinæ are far more specialized than the American species of Peripatidæ, we may assume that the connection between southern South America and the Australian region persisted to a much later date than that by which the Peripatidæ arrived from Africa.

Although, judging from what we know of the other elements of the faunas of Australia, Tasmania, and New Zealand, it is easy to understand how the Peripatoidinæ entered southern South America from the Australian region, it is not so easy to understand how they entered South Africa, unless we are willing to assume that there has been a connection between South Africa and Antarctica by way of the Crozet and Kerguelen Banks, which was more or less contemporaneous with that between southern South America and Antarctica.

The African genus *Opisthopatus* is very closely allied to the American *Metaperipatus,* the alliance being much more close than in the case of the African and American genera of the Peripatidæ. These two genera are less specialized than are the other genera of the Peripatopsidæ, and the explanation at once suggests itself that, besides being later arrivals in America than the genera of the Peripatidæ, they, like *Oroperipatus,* indicate the extreme limits of the area over which their group (the Peripatoidinæ) was at one time dominant, and exist at present in localities with a physico-economically very restricted radius which approaches the physico-economical conditions of the original habitat of their subfamily more closely than does the habitat of any of the more specialized Australian genera, so that they have had but little incentive to change in order to meet new conditions.

If this were so, it would suggest of itself that the Peripatoidinæ in the past had their headquarters in the extreme south, in contrast to the primarily tropical Peripatidæ.

The sharp separation in the distribution of the Peripatoidinæ and the Peripatopsinæ in the East Indian and Australian regions suggests a long and complete separation of the land of which the Moluccas, New Guinea, and New Britain (and southeastern Africa) were once an integral part, from Australia (including Tasmania and New Zealand, but possibly excepting the Torres Strait region), this separation long antedating the separation of Australia from Antarctica, but being subsequent to the isolation of the Malayan region from the Moluccas and the islands farther east.

THE DISTRIBUTION OF THE SPECIES, GENERA AND HIGHER GROUPS OF THE ONYCHOPHORES IN DETAIL

Order ONYCHOPHORA: Malay Peninsula and Sumatra; Ceram; New Guinea; New Britain; Australia, Tasmania and New Zealand; central and southern Africa; Central and South America from Tepic, Mexico, southward to Chile, including the West Indies.

Family PERIPATOPSIDÆ Bouvier, 1904: New Britain, New Guinea and Ceram, Australia, Tasmania and New Zealand; Natal and Cape Colony; Chile.

Subfamily PERIPATOIDINÆ Evans, 1901: Southern Queensland, New South Wales, Victoria and Western Australia; Tasmania and New Zealand; Natal and the adjoining portion of Cape Colony; Chile.

Section I: Southeastern (southern Queensland, New South Wales and Victoria) and Western Australia, Tasmania and New Zealand.

Genus *Peripatoides* Pocock, 1894: Southern Queensland, New South Wales, Victoria and Western Australia, Tasmania and New Zealand.

Viviparous species; *Peripatoides.*

Peripatoides orientalis (Fletcher): Wollongong, Blue Mountains, Moss Vale District, Tamworth, Cassilis (banks of Mounmoun Creek), Burrawang, Colo Vale (near Mattagong), Moree, Illawarra, and Dunoon (near Richmond River), New South Wales; ?Cardwell, ?Brisbane, ?Wide Bay, Queensland; ?Cunningham's Gap, Northern Territory of South Australia.

Peripatoides occidentalis (Fletcher): Bridgetown, Island of Perth, Western Australia.

Peripatoides gilesii Spencer: Lion Mill and Armadale, near Perth; Mundaring Weir, Darling Ranges; and Kimberley, Western Australia.

Peripatoides novæ-zealandiæ (Hutton): Wellington, Dunedin, Nelson, Porirua, Stephen's Island and Oropi-bush (near Taranga), Otago, Woodville, and Jararua, New Zealand.

Peripatoides suteri (Dendy): Stratford and Taranaki, north New Zealand.

Oviparous species; *Ooperipatus.*

Peripatoides leuckarti (Sänger): Northwest of Sydney, New South Wales; Macedon, Sassafras Gully, Ferntree Gully, and Gembrook, Victoria.

Peripatoides spenceri Cockerell: Mt. Wellington, district of Lake St. Clair, Tasmania.

Peripatoides viridimaculatus (Dendy): End of Lake Te Anau, Clinton Valley, south New Zealand; ?near Te Aroha, north New Zealand.

Oviparous species; *Symperipatus.*

Order Onychophora—Continued.

Family Peripatopsidæ Bouvier, 1904—Continued.

Subfamily Peripatoidinæ Evans, 1901—Continued.

Section I—Continued.

Genus *Peripatoides* Pocock, 1894—Continued.

Peripatoides oviparus (Dendy): Warburton (on the upper Yarra), Brown Hill (near Ballarat), Macedon, Valhalla, Mt. Baw Baw, Pyalong, Warragul (Gippsland), Victoria; Mt. Kosciusko (Wilson's Valley, at an altitude of 5,000 feet, and also at an altitude of 5,700 feet), and between Exeter and Bundanoon (Moss Vale district), New South Wales; Cooran, Cardwell and Brisbane, Queensland; Cunningham's Gap, northern territory of South Australia.

Section II: Natal, and the adjoining portion of Cape Colony; Chile.

Genus *Opisthopatus* Purcell, 1899: Natal, and the adjoining portions of Cape Colony.

Opisthopatus cinctipes Purcell: Vicinity of Dunbrody, Uitenhage Division, Cape Colony; Doornek, Zuurberg Range, Alexandria Division, Richmond and Durban, Natal.

Genus *Metaperipatus* A. H. Clark, 1913: Chile.

Metaperipatus blainvillei (Blanchard): Chiloë Island; near Villa Rica; near Corral; Enero, in the Cordillera Pelada, province of Valdivia; Contulmo, Cordillera of Nahuelbuta, which separates the provinces of Malleco and Arauco; valley of Buchoco, between Lake Lanalhue and the sea, south of Cañete, 10 kilometers from Contulmo; all the localities are in southern Chile.

Metaperipatus umbrinus (Johow): Near Zapallar, on the coast of Aconcagua province, in 32° 33′ 20″ S. lat.

Subfamily Peripatopsinæ Evans, 1901: New Britain, New Guinea and Ceram; Natal and Cape Colony.

Section I: Cape Colony and Natal.

Genus *Peripatopsis* Pocock, 1894: Cape Colony and Natal.

Peripatopsis sedgwicki Purcell: Plettenberg Bay (Knysa), Port Elizabeth and Grahamstown, Cape Colony.

Peripatopsis moseleyi (Wood-Mason): Vicinity of King William's Town, East London, Katberg Forest (50 miles northwest of King William's Town), Pirie Bush (near King William's Town), Dias, and vicinity of Port Elizabeth, Cape Colony; Pietermaritzberg and vicinity, Eastcourt and vicinity, Richmond, Aslockton (Dronkvlei, near Umzimkulu River, Ixopo District), and Riet Vlei (in the west of Umvoti District), Natal.

Peripatopsis clavigera Purcell: Knysa, eastern part of Cape Colony.

Order ONYCHOPHORA—Continued.

Family PERIPATOPSIDÆ Bouvier, 1904—Continued.

Subfamily PERIPATOPSINÆ Evans, 1901—Continued.

Section I—Continued.

Genus *Peripatopsis* Pocock, 1894—Continued.

Peripatopsis leonina Purcell: Lions Hill, and the shores of Table Bay.

Peripatopsis balfouri (Sedgwick): Vicinity of Cape Town; Table Mountain; Platteklip and Newlands ravines, Table Mountain; ravines near Camp's Bay and Hout Bay; Simons Town, St. James, on the shore of False Bay; Cedar Mountains; Clanwilliam, at Boschkloof waterfall; Constancia (Plettenberg Bay), Cape Colony.

Peripatopsis capensis (Grube): Vicinity of Cape Town, Constancia, Mowbray, Table Mountain, Platteklip, St. James (False Bay), Wynberg, Newlands, Randebosch, Frenchhoek (division of Paarl), Caledon, Houw Hoek, Hottentots Holland Mountains (division of Caledon), and Swellendam, Cape Colony.

Section III: New Britain, New Guinea and Ceram.

Genus *Paraperipatus* Willey, 1898: New Britain, New Guinea and Ceram.

Paraperipatus novæ-britanniæ (Willey): New Britain.

Paraperipatus schultzei Heymons: German New Guinea, on a mountain in the interior at an altitude of 1,570 meters.

Paraperipatus schultzei var. *ferrugineus* Heymons: German New Guinea, on a mountain in the interior at an altitude of 1,570 meters.

Paraperipatus lorenzi Horst: South Dutch New Guinea, in the Wichmann mountains, at an altitude of 10,000 feet.

Paraperipatus papuensis Sedgwick: North Dutch New Guinea, in the Arfak mountains at Sarayu, at an altitude of 3,500 feet.

Paraperipatus ceramensis (Muir and Kershaw): Peroë (Piru), western Ceram.

Family PERIPATIDÆ Evans, 1902: Malay Peninsula and Sumatra; French Congo; tropical America from Tepic, Mexico, southward to Sorata, Bolivia, and eastward, on the Atlantic coast ranging from Rio de Janeiro to and throughout the West Indies.

Subfamily EOPERIPATINÆ A. H. Clark: Sumatra and the Malay Peninsula.

Genus *Eoperipatus* Evans, 1901: Sumatra and the Malay Peninsula.

Eoperipatus weldoni Evans: Malay Peninsula; Mt. Bukit Besar, on the border between Nawngchick and Jalor, 1,000 meters; Larut, 1,220 meters.

Order ONYCHOPHORA—Continued.

Family PERIPATIDÆ Evans, 1902—Continued.

Subfamily EOPERIPATINÆ A. H. Clark—Continued.

Genus *Eoperipatus* Evans, 1901—Continued.

Eoperipatus horsti Evans: Malay Peninsula; Kuala Aring, state of Kelantan.

Eoperipatus sumatranus (Sedgwick): East coast of Sumatra.

Genus *Typhloperipatus* Kemp, 1913: Extreme southeastern corner of Tibet.

Typhloperipatus williamsoni Kemp: Near Rotung, on the banks of the Dihang River (in Tibet, very near the northern corner of Assam); 1,200 to 2,500 feet.

Subfamily PERIPATINÆ Evans, 1902 (emended A. H. Clark, 1913): tropical America; French Congo.

Genus *Mesoperipatus* Evans, 1901: French Congo.

Mesoperipatus tholloni (Bouvier): Ngômô, Ogôoué, French Congo.

Genus *Peripatus* Guilding, 1825: Tropical America, except in a few localities in the mountains of Colombia, Panamá and Costa Rica east of the Atlantic-Pacific watershed, from Vera Cruz, Mexico, and Guatemala on the north to Rio de Janeiro on the south, including the West India islands.

Subgenus *Macroperipatus* A. H. Clark, 1913: Rio de Janeiro, Brazil, French and British Guiana, and Trinidad, westward to Panamá, and northward to Vera Cruz, Mexico.

Macroperipatus ohausi (Bouvier): Near Rio de Janeiro, Brazil.

Macroperipatus geayi (Bouvier): French Guiana; La Chorrera, Panamá.

Macroperipatus guianensis (Evans): Demerara, British Guiana.

Macroperipatus torquatus (von Kennel): Trinidad.

Macroperipatus perrieri (Bouvier): Vera Cruz, Mexico.

Subgenus *Epiperipatus* A. H. Clark, 1913: Santarem, Brazil, French, Dutch and British Guiana, Trinidad, Tobago and Grenada, westward to Central America, ranging northward to Guatemala.

Epiperipatus brasiliensis (Bouvier): Santarem, Brazil, Mérida, Venezuela and San Pablo, Panamá.

Epiperipatus simoni (Bouvier): Island of Marajó, at the mouth of the Amazons; Caracas, Venezuela.

Epiperipatus edwardsii (Blanchard): French and Dutch Guiana, and possibly Trinidad, westward to Panamá and Darien.

Epiperipatus imthurmi (Sclater): British, French and Dutch Guiana.

Epiperipatus evansi (Bouvier): Demerara, British Guiana.

Epiperipatus trinidadensis (Stuhlmann): Trinidad.

Order Onychophora—Continued.

Family Peripatidæ Evans, 1902—Continued.

Subfamily Peripatinæ Evans, 1902 (emended A. H. Clark, 1913)—Continued.

Genus *Peripatus* Guilding, 1825—Continued.

Subgenus *Epiperipatus* A. H. Clark, 1913—Continued.

Epiperipatus trinidadensis var. *broadwayi* A. H. Clark: Tobago.

Epiperipatus barbouri (Brues): Grenada.

Epiperipatus isthmicola (Bouvier): Costa Rica.

Epiperipatus biolleyi (Bouvier): Costa Rica; ?British Honduras.

Epiperipatus biolleyi var. *betheli* Cockerell: Puerto Barrios, Guatemala.

Epiperipatus nicaraguensis (Bouvier): Nicaragua.

Subgenus *Plicatoperipatus* A. H. Clark, 1913: Jamaica.

Plicatoperipatus jamaicensis (Grabham and Cockerell): Jamaica.

Subgenus *Peripatus* Guilding, 1825: West India islands of Jamaica, Haiti, Puerto Rico, Vieques, St. Thomas, Antigua, Guadeloupe, Dominica and St. Vincent; mountains of western Venezuela westward to Colombia, northward to Panamá and Costa Rica.

Peripatus swainsonæ Cockerell: Jamaica.

Peripatus haitiensis Brues: Near Furcy, Haiti.

Peripatus manni Brues: Furcy, Haiti.

Peripatus juanensis Bouvier: Puerto Rico and Vieques.

Peripatus danicus Bouvier: St. Thomas.

Peripatus antiguensis Bouvier: Antigua.

Peripatus bavayi Bouvier: Guadeloupe.

Peripatus dominicæ Pollard: Dominica.

Peripatus juliformis Guilding: St. Vincent.

Peripatus brölemanni Bouvier: Tovar, Raxto Casselo and Puerto Cabello, Venezuela.

Peripatus sedgwicki Bouvier: Caracas, San Esteban, La Moka, Las Trincheras and La Guayra, Venezuela.

Peripatus bouvieri Fuhrmann: Boca del Monte, near Bogotá, Colombia.

Peripatus ruber Fuhrmann: Rancho Redondo, Costa Rica; Lino, near Bouquete province of Chiriqui, Panamá, 4,100-4,500 feet elevation.

Genus *Oroperipatus* Cockerell, 1908: Excepting for localities in Colombia and western Brazil, restricted to the Pacific watershed of tropical America, from Tepic, Mexico, southward to Sorata, Bolivia.

Oroperipatus eiseni (Wheeler): Tepic, Mexico, south to the Rio Purus, Brazil.

Oroperipatus soratanus (Bouvier): Sorata, Bolivia.

Oroperipatus intermedius (Bouvier): Sorata, Bolivia.

Order ONYCHOPHORA—Continued.

Family PERIPATIDÆ Evans, 1902—Continued.

Subfamily PERIPATINÆ Evans, 1902 (emended A. H. Clark, 1913)—Continued.

Genus *Oroperipatus* Cockerell, 1908—Continued.

Oroperipatus balzani (Camerano): States of Coroico and Chulumani, Bolivia.

Oroperipatus corradoi (Camerano): Quito, Balzar and Guayaquil, Equador; Ancon, Panama Canal Zone.

Oroperipatus belli (Bouvier): Duran (Guayas River), Equador.

Oroperipatus quitensis (Schmarda): High regions of Equador.

Oroperipatus cameranoi (Bouvier): Cuenca and Sigsig, Equador.

Oroperipatus lankesteri (Bouvier): Paramba, near Quito, Equador.

Oroperipatus ecuadoriensis (Bouvier): Bulim, northwestern Equador.

Oroperipatus tuberculatus (Bouvier): Popayan, Colombia.

Oroperipatus multipodes (Fuhrmann): Rio Amago, Colombia.

Oroperipatus bimbergi (Fuhrmann): Amagatal (900-1,800 meters) and Guaduas (800 meters), Colombia.

Oroperipatus goudoti (Bouvier): Mexico.

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THE DEVELOPMENT OF THE LUNGS OF THE ALLIGATOR

(With Nine Plates)

BY

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THE DEVELOPMENT OF THE LUNGS OF THE ALLIGATOR

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(With Nine Plates)

As in the chick, the primordia of the lungs in the alligator are budded off from the ventral side of the pharynx just caudad to the region of the gill clefts. They are first seen in embryos of about thirty somites, slightly younger than the one shown, in outline, in figure 1. (The figures are arranged consecutively on plates at end of paper.)

Figure 7 represents a wax reconstruction of the respiratory tract of an embryo of the stage shown in figure 1. Four gill clefts and about thirty-five somites are present in this embryo; but the buds of the appendages are not yet visible. The allantois is evident, just anterior to the tail, but the yolk stalk was torn away and hence is not shown in the figure.

In the embryo from which this reconstruction was made the right bronchial bud was considerably thicker than the left, but extended only about half as far caudad. It is frequently the case that one bronchial bud pushes caudad faster than the other. The planes of the sections are indicated by the numbers 2 to 6, in figure 7.

Figure 2 represents a section through the pharynx, in the region of the last gill cleft, *c*, of the stage under discussion. As seen in the figure, the epithelium of the cleft is here continuous with that of the pharynx, though there is no opening at this point. This section is at the anterior end of the deep, median depression, *g*, in the floor of the pharynx which extends from this point caudad for a considerable distance, and is called by Lillie the laryngo-tracheal groove. This groove is deep, and is so narrow that its cavity is a mere vertical slit; it is open throughout its length to the trachea above. At its posterior end the groove suddenly becomes less deep and widens out, as shown in figures 3 and 7. The plane, 2, of this section is in the region of the extreme anterior end of the reconstruction, figure 7. The lining of all these cavities consists, at this stage, of a compact, stratified epithelium, six or more cells deep.

The structures surrounding those under discussion are shown, but need no description.

Figure 3 shows a section at the point of separation of the trachea, *t*, from the pharynx or œsophagus, *œ*.

Figure 4, six sections caudad to figure 3, shows the trachea primordium, *t*, distinct from the œsophagus, *œ*. The latter has here a circular outline, while the former is much wider from side to side.

Figure 5 is a few sections caudad to figure 4, and shows the trachea at its point of division into the two bronchial primordia, *b*. The œsophagus, *œ*, has the same appearance as in the preceding figure.

Figure 6 is a few sections caudad to figure 5, and represents the two bronchi, *b*, as widely separated from the œsophagus and from each other. As noted above, the right bronchus is of considerably greater diameter than the left, but, as shown in figure 7, it does not extend so far caudad. The epithelium is of the same character as in the more anterior sections.

The entodermal bronchial primordia are surrounded by a rounded mass of pulmonary mesoblast, *m*, that bulges laterally into the crescentic pleural cœlom, *pl*, on each side.

Figure 8 represents a reconstruction on paper of the pulmonary tract of a slightly later stage. The pharynx, *p*, shows the same deep groove in the post-pharyngeal region that was noted in the preceding stage. It rather suddenly divides into the dorsal œsophagus, *œ*, and the ventral trachea, *t*. The œsophagus gradually enlarges as it passes caudad; the trachea, which now extends through a number of sections, diminishes slightly in caliber to its point of division into the two bronchi, b, b^1. Each bronchus is rather irregular in shape, but gradually increases in diameter to form an enlargement near its posterior end. In the embryo here represented the right bronchus, *b*, was of greater caliber but of less length than the left, b^1. At the point of separation from the trachea the bronchi lie at a considerable distance ventrad to the œsophagus, but as they pass caudad they gradually approach the horizontal plane of the œsophagus until they lie practically on each side of it. The histological structures are about the same as in the preceding stage so that no sections of this stage need be figured.

Figure 9 represents, in outline, an embryo of the next stage to be described. The appendages are here well developed and the face is beginning to assume form.

Figure 10 is a camera sketch of a wax reconstruction of the entodermal respiratory tract of the embryo shown in figure 9. The

extreme right of the figure is in the posterior region of the pharynx, where the trachea begins to separate from the œsophagus. As may be seen in cross sections, the pharynx is here of a crescentic outline, convex dorsally, and hence is much smaller in cross section than it seems in the figure under discussion. Projecting caudad and ventrad from the horns of the crescent (figures 10, 11 and 12) are one or more hollow, cylindrical bodies, perhaps the so-called epithelial vestiges. The largest and most posterior of these, on the right side is shown at *e* in figure 10. It is quite a conspicuous projection, somewhat swollen near its distal end, lying laterad and somewhat ventrad to the base of the trachea; its mate of the left side is not shown in figure 10. The other epithelial vestiges are smaller and are not represented in this figure; they may be discussed in a later paper. The trachea, *t*, after separating from the œsophagus, *œ*, extends caudad for some distance before it divides into the two bronchi, b, b^1. Its anterior region lies parallel to and fairly close to the œsophagus, but at its point of divergence into the bronchi it bends ventrad, so that the bronchi lie at a considerable distance below the œsophagus.

At this stage each endothelial lung rudiment consists of three main lobes, l^1 to l^3, which project dorsad, on each side of the œsophagus, at the region where the latter enlarges and passes ventrad into the stomach, *s*. The mesoderm of the lungs is not lobulated.

Figures 11 to 18 represent transverse section through the respiratory tract in the planes shown on figure 10.

Figure 11 passes through the posterior region of the pharynx, *p*, where it still retains a somewhat crescentic outline, at the point of origin of the trachea, or glottis, *gl*. The epithelium is here comparatively thin and the cavity of the pharynx comparatively spacious. Around the glottis a condensation of mesoblast, *la*, represents the beginning of the larynx. Dorsad and laterad to the pharynx a cylindrical mass is the thymus, *ty*, while one of the epithelial vestiges is shown at *e*. The spinal cord, notochord, etc., may be recognized in this section, but need not be discussed here.

Figure 12 is through the point of separation of the trachea and œsophagus. The deep depression from the floor of the pharynx is here widening to form a tube, *t*, the trachea. The pharynx, *p*, is still of crescentic outline and its cavity is much reduced in extent. The thymus *anlage*, *ty*, appears the same as in the preceding figure, while the epithelial vestige, *e*, here shown is on the right instead of the left side.

Figure 13 is through the region just caudad to the point of separation of trachea, *t*, and œsophagus, *œ*. The former is here a cylindrical tube with a lumen of considerable diameter, while the latter is still crescentic in cross section and has no lumen at all. This solid region of the œsophagus extends through a considerable number of sections, and the fusion of the dorsal and ventral walls is so complete that, even under high power, no indication of the line of fusion is visible. At one side of the trachea is still seen the epithelial vestige, *e*.

Figure 14 represents a section through the middle region of the trachea, *t*, which has here about the same external diameter as in the preceding figure; but, owing to the thicker walls, its lumen is narrower than in the more anterior section. This section is just caudad to the solid region of the œsophagus, *œ*, and shows the reappearance of the lumen as a small, circular opening at each lateral end of the now dumbbell-shaped œsophagus. A very small, irregular space is seen above and below the nearly solid œsophagus, as though it had shrunk away from the surrounding tissue.

Figure 15 shows a section passing through the embryo at the point of division of the trachea into the two bronchi, *b*. At this point the triangular, combined areas of the two bronchi are considerably greater than that of the trachea.

The mesoblast immediately surrounding the bronchi is considerably denser than the general mesoblast of this region. A similar, but less marked, condensation of the mesoblast is seen around the trachea anterior to this region. The œsophagus, *œ*, is here cylindrical and exhibits a large lumen.

Figure 16 represents a section through the bronchi, *b*, just cephalad to the region where they expand to form the first lung lobule, l^1, figure 10. The bronchi here are much larger in diameter than the œsophagus, *œ*, and each is surrounded by a narrow zone of dense mesoblast. In cross section the bronchi are circular, and their walls and that of the œsophagus are composed of a compact epithelium of three or four layers of cells. At this point the œsophagus and two bronchi lie at the angles of a nearly equilateral triangle.

Figure 17 passes through the second pulmonary lobe, l^2, figure 10. That the section does not seem to quite fit the reconstruction is due partly to the angle at which the reconstruction was drawn and partly to a slight falling ventrad of the lungs and trachea, owing to the softening of the wax. The œsophagus, *œ*, is here considerably larger than in the preceding section, is compressed laterally, and lies

immediately between the lungs on either side. The irregular outlines of the lungs and the variation in the thickness of their walls are due, of course, to the plane of the section. The surrounding zone of dense mesoblast is narrower than in the preceding section.

Figure 18 passes through the third and most posterior lobe, l^3, figure 10, of the lung. At this point the œsophagus, *œ*, bends sharply ventrad and rapidly enlarges to form the stomach, *s*. On the right the lung is so cut as to exhibit two cavities, almost at their point of union: a small, dorsal lobule, and a larger, ventral one; on the left the two lobules are cut caudad to their junction, and the upper one is cut through its extreme caudal wall so that its cavity does not appear in the section. The walls are of the same character as in the preceding section, and the dense layer of surrounding mesoblast is even narrower than in the more anterior section.

In this section a small mass of Wolffian tubules, *Wt*, is seen on each side of the aorta and dorsal to the lungs; while both in this and in the preceding two sections the dorsal region of the liver is seen in the lower part of the section, *li*.

Figure 19 represents a reconstruction, on paper, of the endodermal lung of the right side (together with the trachea and œsophagus), of a later stage than the preceding. While the endodermal lung here shows this comparatively complicated series of lobules, the surrounding mesoderm (not shown in figure 19) is still smooth in outline and free from lobules as might be expected from the smooth, unlobulated condition of the adult lung. The extreme right of the figure begins just anterior to the lung and shows the œsophagus, *œ*, and trachea, *t*, the latter being now of much smaller diameter than the former; in the preceding stage they were of about the same caliber. In relation to the size of the lungs the trachea is now of much smaller diameter than before; it is of considerably greater length, though only its posterior part is shown in the figure. The point of division into the two bronchi is at the plane of the line 21, but only one bronchus is shown in the figure. The point of emergence of the bronchus into the lung is in the plane of line 22. At the left of the figure the œsophagus, *œ*, is of much greater caliber than at the more anterior end, but the difference is not so great as is apparent in figure 19, because at the anterior end the long axis of the cross section is horizontal, while at the posterior end it is nearly vertical. Projecting cephalad are seen seven or eight larger lobules of various sizes and shapes, some of which bear secondary lobules; projecting caudad are only five or six lobules, most of which

are smaller than those of the anterior end. Some of the very small secondary lobules are not shown in this figure.

Figure 20 represents a transverse section through line 20 of figure 19; only the respiratory tract and immediately surrounding structures are shown. In the center of the figure is seen the very large œsophagus, *œ*, below which is the relatively narrow trachea, *t;* the epithelium of the former consists of only two or three layers of cells; that of the trachea consists of about four or five layers. Surrounding both tubes is a fairly thick layer of condensed mesoblast; that surrounding the œsophageal epithelium consists of more or less elongated or spindle-shaped cells; that around the tracheal epithelium consists of closely arranged spherical cells. Projecting dorsad and laterad from the undifferentiated mesoblast that surrounds the œsophagus and trachea are two rounded masses, the mesodermal lung primordia, *m.* The mass on the left of the figure is the one shown in figure 19; it is larger than the one on the right and exhibits two lobules of the entodermal lung primordia, *l,* while on the right only the anterior end of a single entodermal lobule is shown. The entoderm of these lobules usually consists of a single layer of rounded cells, but immediately surrounding this entoderm is a thin, dense layer of somewhat flattened mesoderm cells. With the low power, under which the figures are drawn, the entodermal and mesodermal cells cannot be distinguished from each other. In the mesoderm surrounding the layers just described may be seen many small dark areas, *c;* these are the *anlagen* of the pulmonary blood vessels.

Figure 21 shows a section through the point of division of the trachea into the two bronchi, *b* (line 21 of figure 19); each bronchus is of as great diameter as the trachea of the preceding figure. The œsophagus, *œ,* has the same general appearance as in the preceding figure, but has increased somewhat in cross section. The mesodermal lung primordia, *m,* are here much larger than in the preceding section and that on the left is again larger than the one on the right; neither shows any division into lobes. On the left are seen three large and several smaller entodermal primordia, $l^{1\ 2}$, while on the right two large and one small entodermal cavities, l^3, are seen.

Figure 22 represents a section through line 22 of figure 19; it passes through the point of emergence of the bronchi, *b,* into the lungs. On the left the bronchus is seen opening into the most ventrally located entodermal cavity, l^1. On the right the section is just cephalad to the corresponding opening. The œsophagus, *œ,* is

somewhat larger in cross section than in the preceding figure, and the lungs have a greater area than in any other section; they extend from the level of the lower side of the œsophagus to nearly the level of the ventral side of the notochord, *n*. Each lung shows several small and two large entodermal cavities; the mesoderm is still without lobules, and is continuous mesially and ventrally with the mesoderm that surrounds the œsophagus. The entire lung of the right side is not shown in the figure; it has the same general outline as that of the left side.

The wall of the œsophagus at this stage is seen, under higher power, to consist of a thin lining epithelium and a dense layer of surrounding mesoblast, the latter being, on an average, about four times as thick as the former. The epithelium, *ep*, consists of one or two layers of cubical cells; the basal cells are usually the larger. The surrounding mesoblastic layer, *ml*, consists of flattened cells that are evidently turning into fibers, and lie with their long axes parallel to the epithelial layer.

The walls of the trachea and bronchi consist of the same two layers, but the epithelium is much thicker than that of the œsophagus, and consists of three or four layers of cells, the basal cells being again much larger than those nearer the lumen.

The mesoblastic layer is of about the same thickness as that of the œsophagus but consists of closely packed spherical cells instead of the elongated cells seen in the former place.

The lung cavities are lined by a thin epithelium which consists, in most places, of a single layer of cuboidal cells; in many places, however, are seen cresentic thickenings which consist in their thickest part, of four or five layers of cells. These crescents are usually seen in the bottoms of the smaller diverticula from the main lung cavities. Surrounding the epithelial lining is a thin, indistinct layer of slightly condensed mesoblast, scarcely discernible under the low power used in drawing this series of figures.

Figure 23 shows the conditions that are to be seen at a plane about half way between the openings of the bronchi and the posterior ends of the lungs, line 23, figure 19. The œsophagus, *œ*, is very large in this region and might, perhaps, be called the stomach, since, ventrad to it, is seen the liver, *li*. In the upper part of the figure are seen two masses of Wolffian tubules, *Wt*, attached to the mesentery on either side of the dorsal aorta, *a*.

The two lungs are of somewhat smaller area than in the preceding section and that on the right shows an indication of a division into a mesodermal lobe at l^3. Part of the lung on the right side is not

included in this figure. The main entodermal cavity on the right side is very irregular in outline and is surrounded by several smaller lobules which are not indicated in the reconstruction.

Figure 24 represents a hasty reconstruction of the mesodermal lung on the right side of an embryo of about seven centimeters length. The lung, *m,* it will be seen, is without division into lobes and is very deep dorso-ventrally, in proportion to its length. The bronchus, *b,* enters it slightly caudad to its middle region. The point of division of the trachea, *t,* into the two main bronchi is in the plane of figure 25. The œsophagus, *œ,* is of large diameter, but its apparently unusual size is partly due to its being laterally compressed.

Figure 25 represents a section through the body of this embryo at the point of division of the trachea, *t,* into the two bronchi, line 25 in figure 24. The skeleton, *aa, ce, r,* is now well outlined in cartilage, and the lungs are approaching their adult condition. The lung on the right side of the figure is somewhat larger than that on the left and exhibits six or eight large endodermal cavities, l, l^1, etc., and numerous smaller ones.

Just ventrad to the œsophagus is the trachea, *t,* with thick walls in which several condensations indicate the formation of the tracheal cartilages, as noted below. Surrounding the trachea are several large pulmonary blood vessels, *bv.*

Figure 26, through line 26 of figure 24, represents a section through the region where the bronchi, *b,* enter the lungs. On the right the bronchus is shown opening directly into the endodermal diverticulum, l^3. Ventrad to the œsophagus, *œ,* and bronchi are several large blood vessels, *bv,* five of which are grouped in a dense mass of mesoblast.

At this stage there has been but little change, histologically, from what was noted in connection with figure 22, though the poor fixation of the material at hand makes it difficult to determine minute details. In the œsophagus the epithelium is about as before, but the surrounding, dense layer of mesoblast now exhibits a faint division into a granular layer, next the epithelium and a more fibrous layer outside of this; the former may represent the submucosa; the latter, the muscular layer, though this point has not been worked out. In the trachea and bronchi the epithelium is thinner than in the preceding stage and consists of only one or two layers of cells. In the surrounding condensed layer of mesoblast may be seen a number of small, darkly stained areas, *ca;* these, under a higher magnification, are seen to consist of a closely-packed

mass of cells, and doubtless represent the *anlagen* of the cartilaginous rings, as noted above. The lung cavities, l^1—l^3, have about the same appearance as described in connection with figure 22, though the epithelium is, perhaps, somewhat thinner, and the crescents are not quite so marked. No attempt has been made to show these details with the low power used in this figure.

Figure 27 represents a ventral view of the body of an alligator of about 15 cm. length, dissected to show the respiratory organs and the neighboring structures.

The trachea, *t,* is seen lying against the ventral wall of the large œsophagus, *œ*; its numerous cartilaginous rings are easily seen. At the anterior end of the trunchus, *tr,* the trachea disappears beneath (dorsad to) the thyroid gland, *tg,* and its division into the two bronchi cannot be seen in this figure. The lungs, *l,* are elongated bodies, lying on each side of and mostly anterior to the heart. Their medial borders are covered by the auricles, *au,* and the thymus glands, *ty,* while the posterior end of each lies beneath (dorsad to) the corresponding lobe of the liver, *li.* The alveolar appearance of the lungs is easily seen with the naked eye. A thymus gland, *ty,* is seen on either side of the posterior region of the trachea; it consists of a lobulated mass posteriorly and of an anteriorly directed cylindrical portion extending forwards into the neck. The heart and liver need not be described here. In the cut surface of the neck may be seen the spinal cord, *sp,* and the notochord, *n,* surrounded by the now cartilaginous vertebral column. The yolk or umbilical stalk, *u,* is shown, somewhat diagrammatically, just caudad to the opened body cavity.

Figure 28 represents, in outline, the respiratory organs of an alligator of about 75 cm. length; this animal was probably two years old and its lungs should have reached approximately their adult condition.

Extending from the glottis, *gl,* at the base of the tongue, *to,* is the fairly wide trachea, *t;* between the lungs it divides symmetrically into the two bronchi, *b,* which enter their respective lungs a little cephalad to the middle region of these organs. The pulmonary veins, *pv,* are shown at the posterior edge of the bronchi; the corresponding arteries are not shown in this figure.

The internal structure of the adult lung has been described by Miller (3) and others and need not be noted here.

The thyroid gland, *tg,* is shown against the trachea just cephalad to the origin of the bronchi.

The material upon which the foregoing work was done was collected by the author in central Florida with the aid of a grant from the Smithsonian Institution.

The embryos were removed from the eggs, in the field, and fixed in various ways. They were sectioned chiefly in the transverse and sagittal planes and were stained, in most cases, with borax carmine and Lyon's blue.

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LETTERING

a, aorta.
aa, anterior appendage.
au, auricle.
b, b′, bronchi.
bv, blood vessel.
c, last gill cleft.
ca, cartilage rings of trachea and bronchi.
ce, centrum.
co, cœlom.
e, epithelial vestige.
ep, epithelium.
g, laryngo-tracheal groove.
gl, glottis.
h, heart.
l′—l,[3] lung or lung diverticula.
la, larynx.
li, liver.
m, mesoblastic lung primordium.
ml, mesoblastic layer.
n, notochord.
œ, œsophagus.
p, pharynx.
pl, pleural cœlom.
pv, pulmonary veins.
r, rib.
s, stomach.
sp, spinal cord.
t, trachea.
tg, thyroid gland.
to, tongue.
tr, trunchus arteriosus.
ty, thymus gland.
u, umbilical cord.
v, ventricle.
Wt, Wolffian tubules.

DESCRIPTION OF FIGURES

Fig. 1.—An outline of an alligator embryo at the beginning of the formation of the lungs.

Figs. 2 to 6.—Transverse section through an embryo of the stage shown in figure 1. The planes of these sections are shown in the reconstruction, figure 7.

FIG. 7.—A wax reconstruction of the respiratory tract of the embryo shown in figure 1.

FIG. 8.—A reconstruction, on paper, of the respiratory tract of an embryo of slightly later development than the one shown in figure 1.

FIG. 9.—An outline of an embryo somewhat older than the one represented in figure 8.

FIG. 10.—A camera sketch of a wax reconstruction of the entodermal respiratory tract of the stage shown in figure 9. The extreme right of the figure is in the region of the pharynx, where the trachea begins to separate from the œsophagus.

FIGS. 11 to 18.—Transverse sections through the respiratory tract in the planes shown on figure 10.

FIG. 19.—A reconstruction, on paper, of the entodermal lung of the right side (together with the trachea and œsophagus) of a later stage than the one represented in figures 10 to 18.

FIGS. 20 to 23.—Transverse sections through the embryo represented in figure 19, in the planes of lines 20 to 23 of that figure.

FIG. 24.—A reconstruction, on paper, of the mesodermal lung on the right side of an embryo of about 7 cm. length.

FIGS. 25, 26.—Transverse sections through the embryo represented in figure 24, in the planes of lines 25 and 26.

FIG. 27.—A ventral view of a dissected embryo of about 15 cm. length, showing the respiratory and other organs.

FIG. 28.—An outline of the respiratory organs of an alligator of about 75 cm. length.

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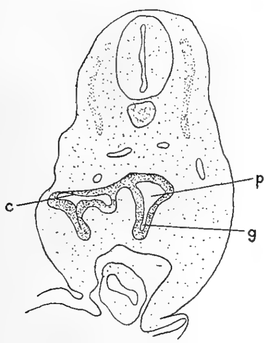

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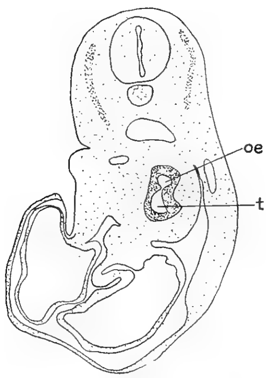

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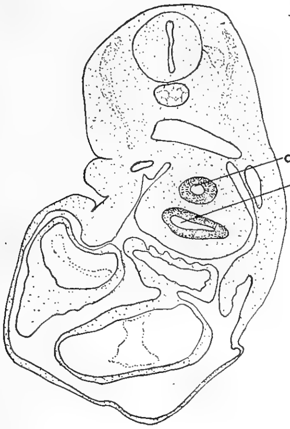
DEVELOPMENT OF LUNGS OF ALLIGATOR



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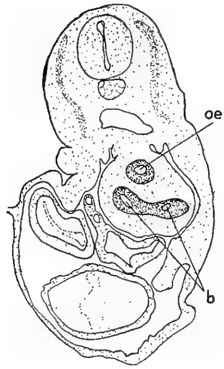

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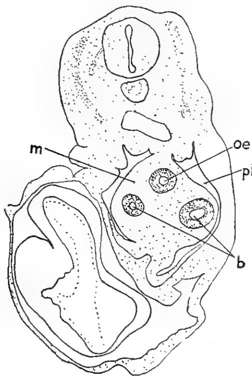

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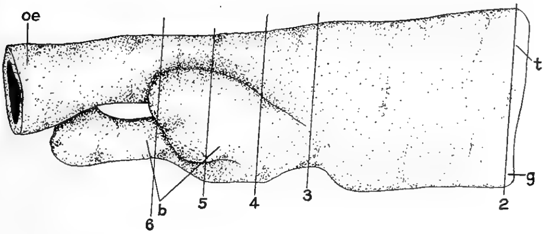

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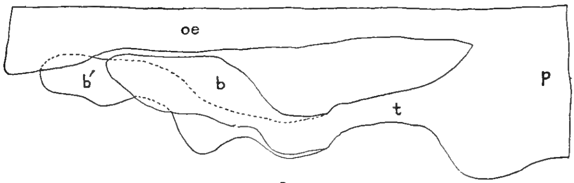
DEVELOPMENT OF LUNGS OF ALLIGATOR



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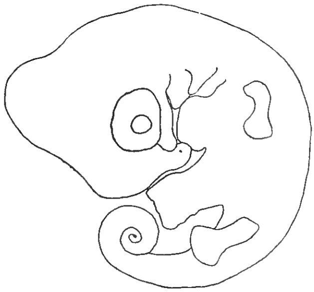

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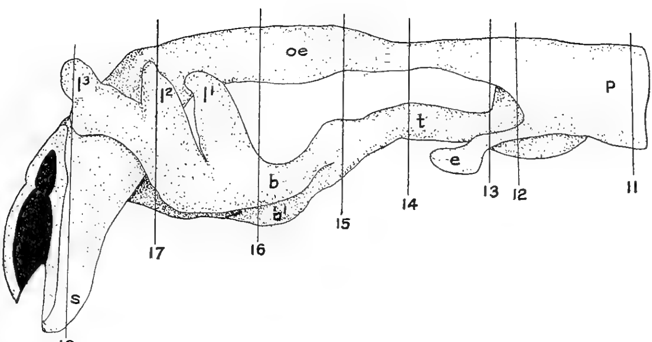

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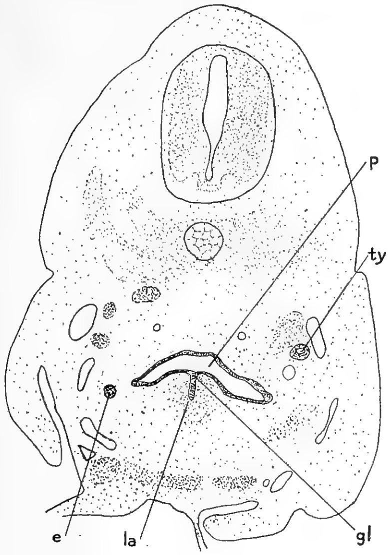
DEVELOPMENT OF LUNGS OF ALLIGATOR



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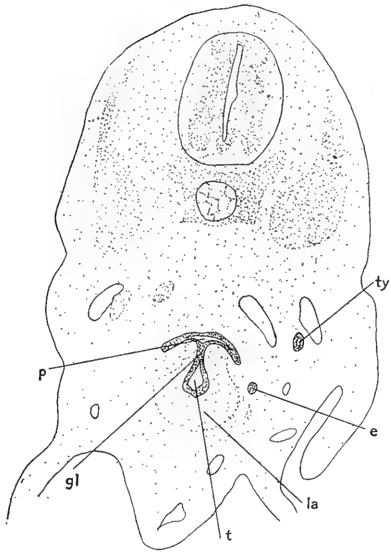

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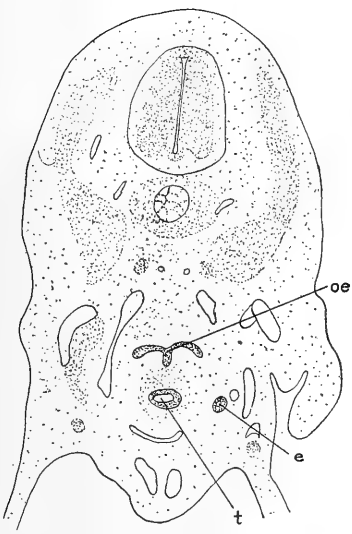

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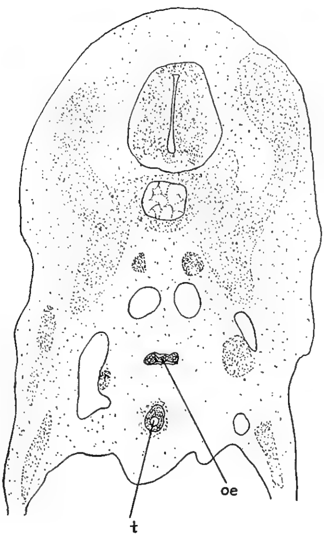

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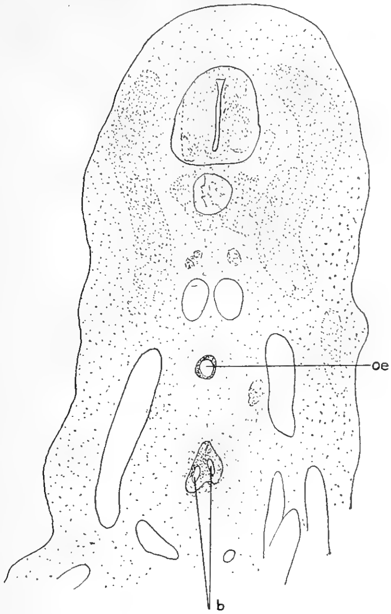
DEVELOPMENT OF LUNGS OF ALLIGATOR



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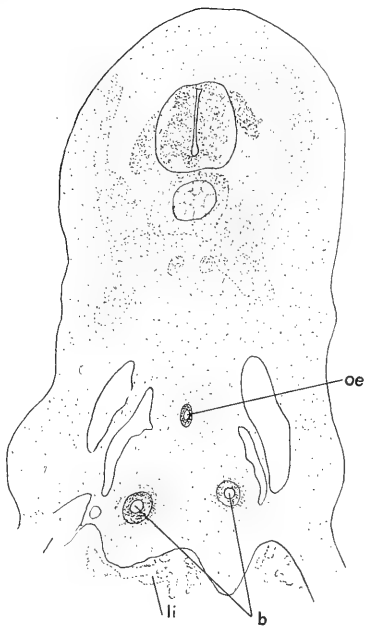

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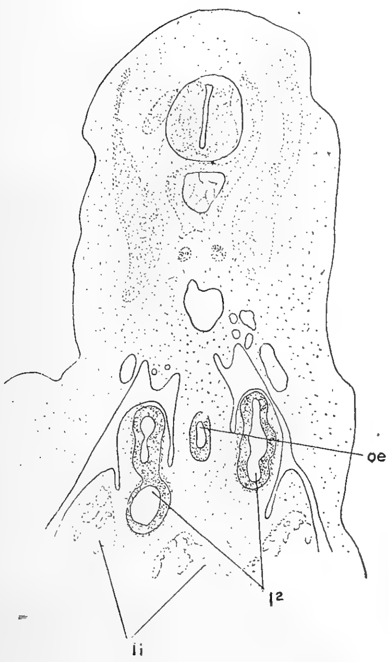

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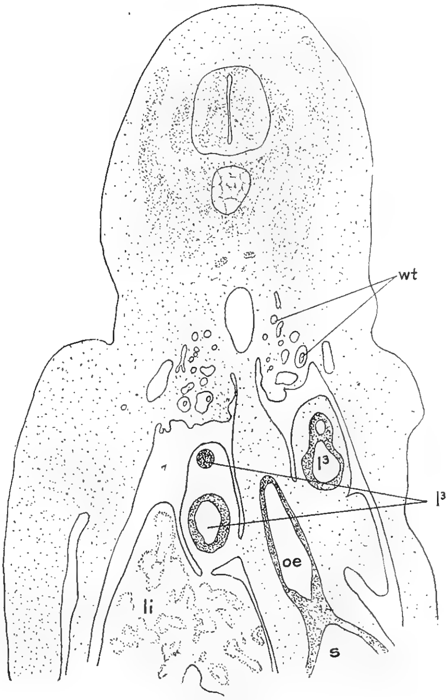

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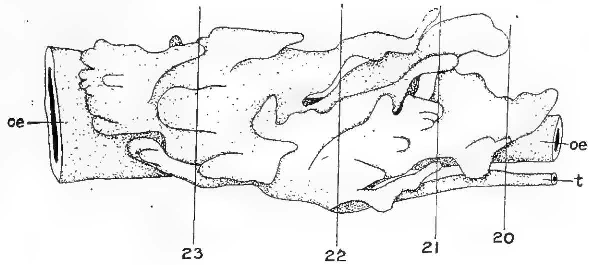
DEVELOPMENT OF LUNGS OF ALLIGATOR



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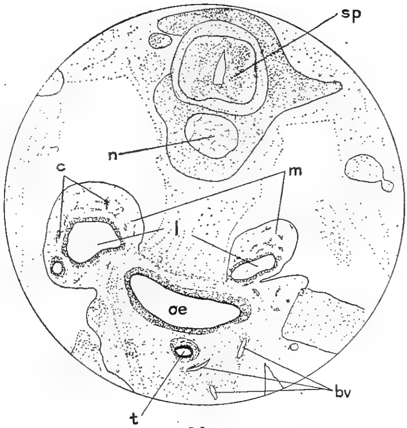

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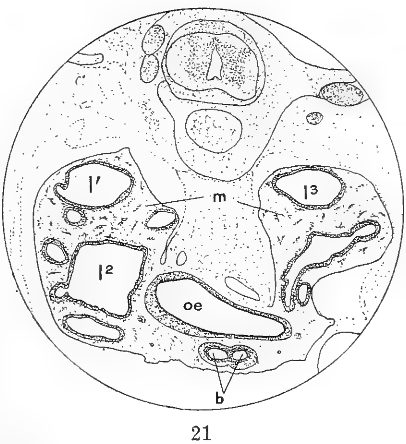

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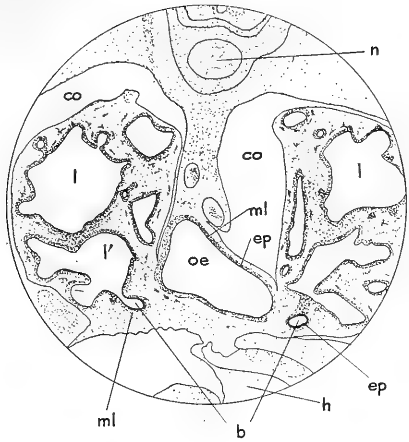
DEVELOPMENT OF LUNGS OF ALLIGATOR



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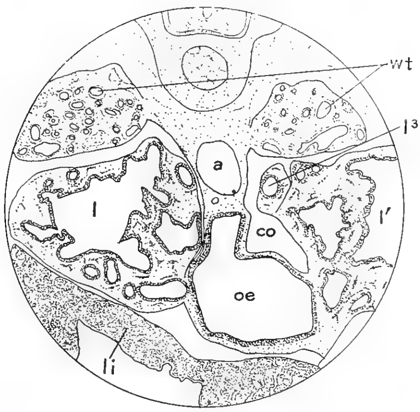

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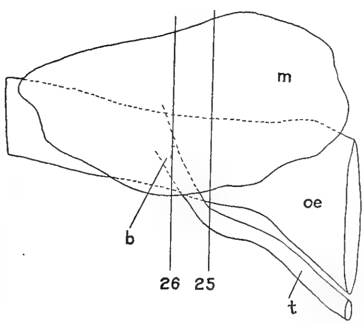

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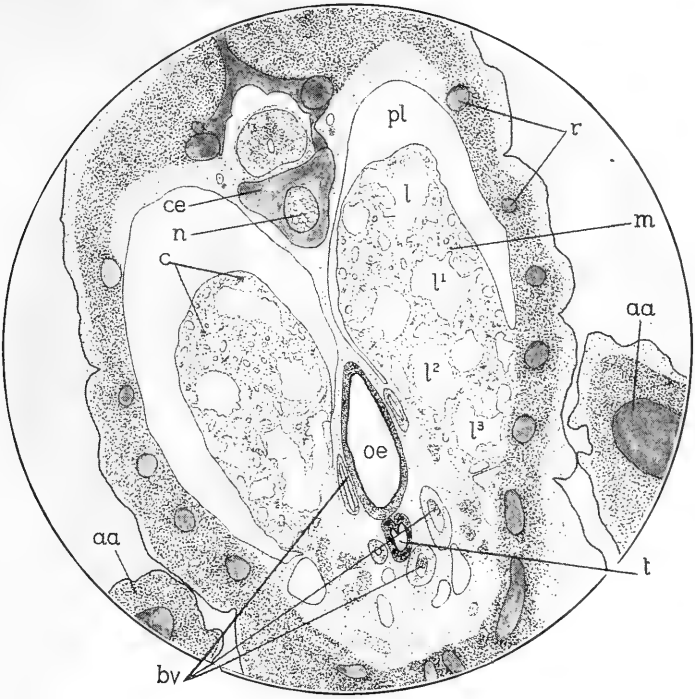
DEVELOPMENT OF LUNGS OF ALLIGATOR



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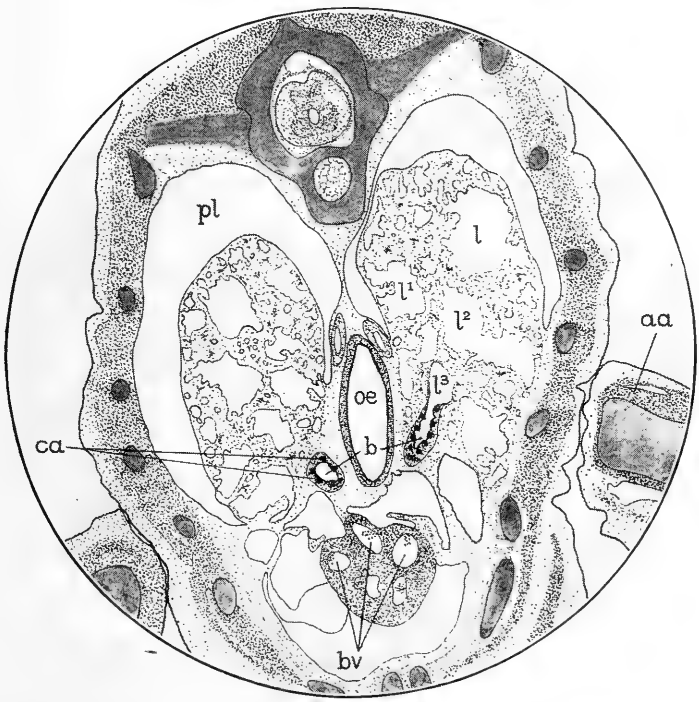
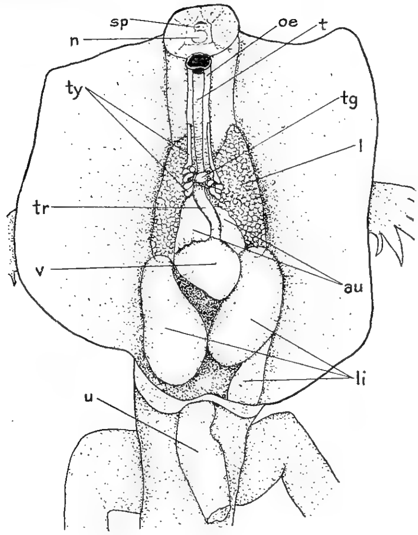


26

DEVELOPMENT OF LUNGS OF ALLIGATOR



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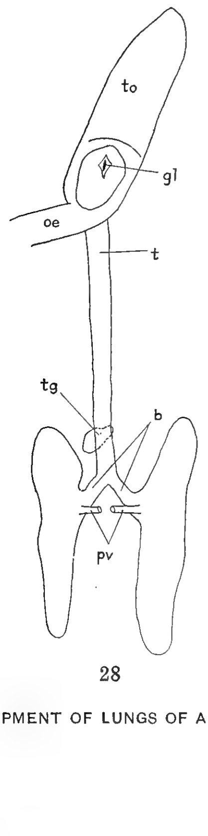

28

DEVELOPMENT OF LUNGS OF ALLIGATOR

SMITHSONIAN MISCELLANEOUS COLLECTIONS
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Hodgkins Fund

A STUDY OF THE RADIATION OF THE ATMOSPHERE

BASED UPON OBSERVATIONS OF THE NOCTURNAL RADIATION DURING EXPEDITIONS TO ALGERIA AND TO CALIFORNIA

BY
ANDERS ÅNGSTRÖM

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PREFACE

The prosecution of the researches described in the following pages has been rendered possible by several grants from the Hodgkins Fund of the Smithsonian Institution, Washington, for which I here desire to express my deep gratitude.

I also stand indebted to various gentlemen for friendly help and encouragement.

In the first place, I wish to express my sincere thanks to my esteemed friend, Dr. C. G. Abbot, Director of the Astrophysical Observatory of the Smithsonian Institution, for the great interest he has shown in my researches. His aid and suggestions have ever been a source of stimulation and encouragement, while his criticisms of my work have never failed to be of the greatest assistance to me.

Other scholars, to whom it is largely due that the observations upon which this study is based have been so far brought to a successful termination that I have been able to draw from them certain conclusions of a general character, are Dr. E. H. Kennard, of Cornell University; Professor F. P. Brackett, Professor R. D. Williams, and Mr. W. Brewster, of Pomona College, California. To all these gentlemen I wish to express my sense of gratitude and my earnest thanks for the valuable assistance they have afforded me in my investigations during the expedition to California.

Ultimately, the value of the observations of nocturnal radiation here published will be greatly enhanced by the fact that the temperature, pressure, and humidity of the atmosphere, up to great elevations, were obtained experimentally by balloon observations made during the expedition from points at or near my observing stations. These observations, made by the United States Weather Bureau in cooperation with the Smithsonian Institution, are given in Appendix I.

It is also of advantage that observations of the solar constant of radiation, the atmospheric transparency for solar radiation, and the total quantity of water vapor in the atmosphere (as obtained by Fowle's spectroscopic method) were made at Mount Wilson during the stay of the expedition. A summary of these results forms Appendix II.

In the present discussion the results of the balloon flights and spectrobolometric work are not incorporated. A more detailed study of the atmospheric radiation, in which these valuable data would be indispensable, may be undertaken more profitably after a determination shall have been made of the individual atmospheric transmission coefficients throughout the spectrum of long wave rays as depending on humidity. This study is now in progress by Fowle and others, and the results of it doubtless will soon be available.

ANDERS ÅNGSTRÖM.

UPSALA, SWEDEN,
December, 1914.

CONTENTS

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SUMMARY

The main results and conclusions that will be found in this paper are the following. They relate to the radiation emitted by the atmosphere to a radiating surface at a lower altitude, and to the loss of heat of a surface by radiation toward space and toward the atmosphere at higher altitudes.

I. The variations of the total temperature radiation of the atmosphere are at low altitudes (less than 4,500 m.) principally caused by variations in temperature and humidity.

II. The total radiation received from the atmosphere is very nearly proportional to the fourth power of the temperature at the place of observation.

III. The radiation is dependent on the humidity in such a way that an increase in the water-vapor content of the atmosphere will increase its radiation. The dependence of the radiation on the water content has been expressed by an exponential law.

IV. An increase in the water-vapor pressure will cause a decrease in the effective radiation from the earth to every point of the sky. The fractional decrease is much larger for large zenith angles than for small ones.

V. The total radiation which would be received from a perfectly dry atmosphere would be about $0.28 \frac{\text{cal.}}{\text{cm.}^2 \text{ min.}}$ with a temperature of 20°C. at the place of observation.

VI. The radiation of the upper, dry atmosphere would be about 50 per cent of that of a black body at the temperature of the place of observation.

VII. There is no evidence of maxima or minima of atmospheric radiation during the night that cannot be explained by the influence of temperature and humidity conditions.

VIII. There are indications that the radiation during the daytime is subject to the same laws that hold for the radiation during the night-time.

IX. An increase in altitude causes a decrease or an increase in the value of the effective radiation of a blackened body toward the sky, dependent upon the value of the temperature gradient and of the humidity gradient of the atmosphere. At about 3,000 meters altitude of the radiating body the effective radiation generally has a maximum. An increase of the humidity or a decrease of the temperature gradient of the atmosphere tends to shift this maximum to higher altitudes.

X. The effect of clouds is very variable. Low and dense cloud banks cut down the outgoing effective radiation of a blackened surface to about 0.015 calorie per $cm.^2$ per minute; in the case of high and thin clouds the radiation is reduced by only 10 to 20 per cent.

XI. The effect of haze upon the effective radiation to the sky is almost inappreciable when no clouds or real fog are formed. Observations in Algeria in 1912 and in California in 1913 show that the great atmospheric disturbance caused by the eruption of Mount Katmai in Alaska, in the former year, can only have reduced the nocturnal radiation by less than 3.0 per cent.

XII. Conclusions are drawn in regard to the radiation from large water surfaces, and the probability is indicated that this radiation is almost constant at different temperatures, and consequently in different latitudes also.

CHAPTER I

PROGRAM AND HISTORY OF THE EXPEDITIONS

It is appropriate to begin this paper with a survey of the external conditions under which the work upon which the study is based was done. Most of the observations here given and discussed were carried out during two expeditions, one to Algeria in 1912, the other to California in 1913. An account of these expeditions will give an idea of the geographical and meteorological conditions under which the observations are made, and it will at the same time indicate the program of the field work, a program that was suggested by the facts referred to in the historical survey of previous work and by the ideas advanced in the chapter on the theory of atmospheric radiation.

In 1912 I was invited to join the expedition of the Astrophysical Observatory of the Smithsonian Institution, led by its Director, Dr. C. G. Abbot, whose purpose it was to study simultaneously at Algeria and California the supposed variations of the radiation of the sun. In May of that year I met Dr. Abbot at Bassour, a little Arab village situated about 100 miles from Algiers, in the border region between the Atlas Mountains and the desert, lying at 1,100 meters above sea level. This place had been selected by Dr. Abbot for the purpose of his observations on the sun, and on the top of a hill, rising 60 meters above the village, his instruments were mounted under ideal conditions. The same place was found to be an excellent station for the author's observations of the nocturnal radiation. A little house was built of boards by Dr. Abbot and myself on the top of the hill. This house, about 2 meters in all three dimensions, was at the same time the living room and the observatory. The apparatus used for the nocturnal observations was of a type which will be described in a later chapter. Its principal parts consist of an actinometer, to be exposed to a sky with a free horizon, a galvanometer, and a milliammeter. At Bassour the actinometer was mounted on the roof of the little observatory, observations of the galvanometer and the ammeter being taken inside. The horizon was found to be almost entirely free. In the north some peaks of the Atlas Mountains rose to not more than half a degree over the horizon, and in the southeast some few sandy hills screened off with their flat wave-like tops a very narrow band of the sky.

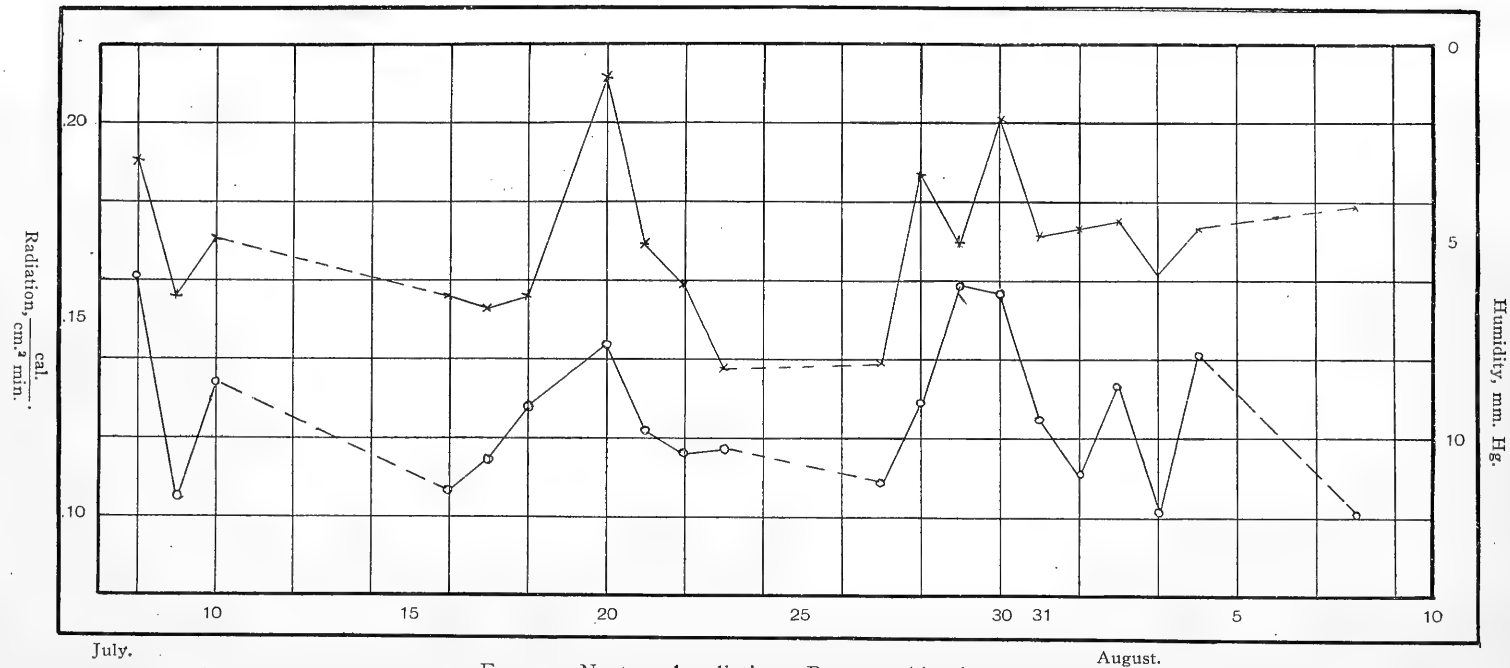

FIG. 1A.—Nocturnal radiation. Bassour, Algeria, 1912.
Radiation, *x*; humidity, *o*.

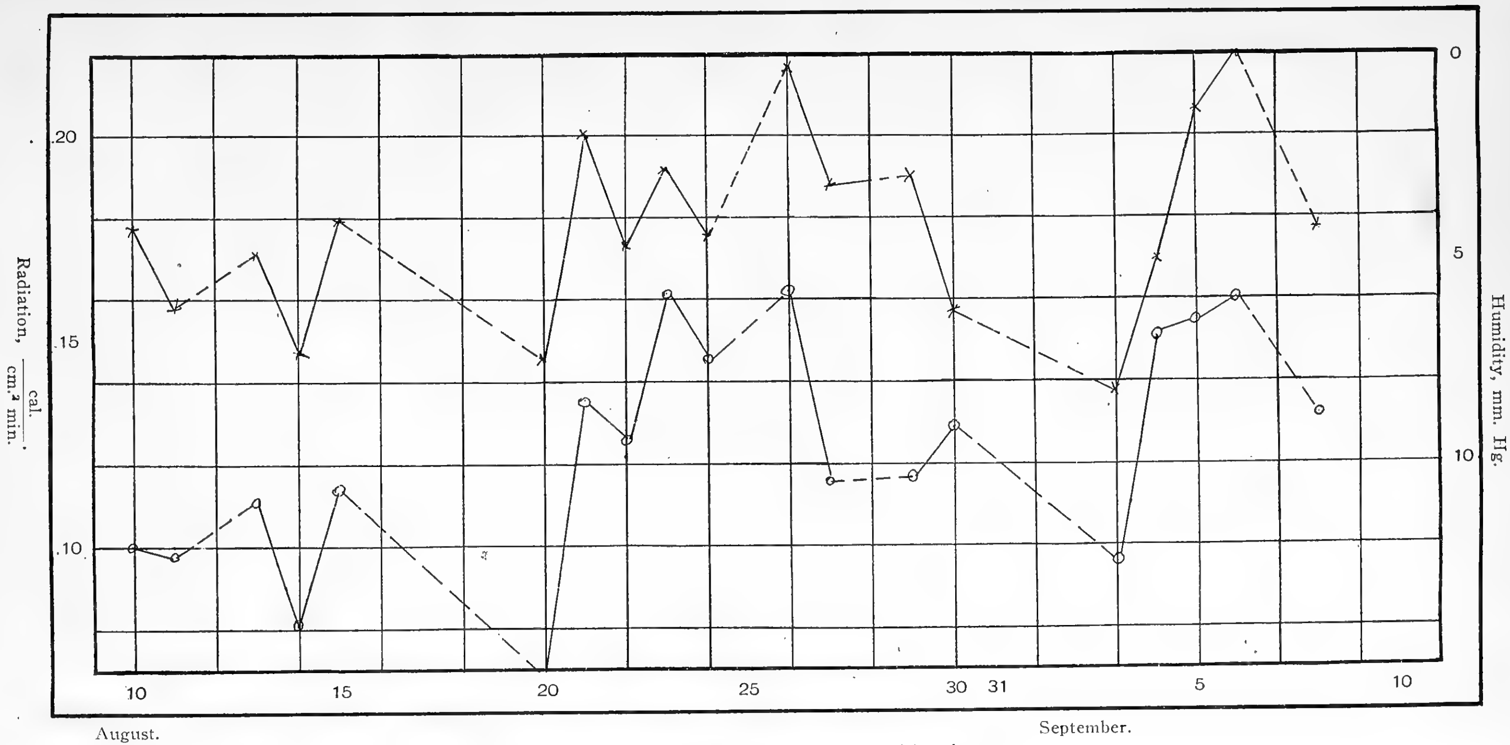

FIG. 1B.—Nocturnal radiation. Bassour, Algeria, 1912.
Radiation, *x*; humidity, *o*.

I was led by several circumstances to think that the nocturnal radiation to the sky would be found to be a function of the water-vapor content of the atmosphere and, as a consequence, observations were made with wet and dry thermometers simultaneously with the measurements of the radiation. In order not to introduce unnecessary influences that might modify this expected effect, it was considered important always to observe under a perfectly clear sky. It was found that a few scattered clouds, far from the zenith, seldom seemed to have any appreciable influence upon the radiation, but, in order not to introduce conditions of the effect of which one could not be quite sure, all the observations made at Bassour and used in this paper were made under a perfectly cloud-free sky. The climatic conditions were favorable for this program, and observations were taken almost every night under a clear sky. Observations were also made of the radiation to different parts of the sky, this study being considered as of special interest in connection with the general problem.

It was my purpose also to make an investigation of the influence of altitude upon the radiation to the sky, and in fact some preliminary measurements were carried out with a view to the investigation of that problem. Thus I made observations one night in the valley of Mouzaia les Mines, situated at the foot of the peak of Mouzaia among the Atlas Mountains, about 15 miles from Bassour. The height of the valley above sea level is 540 meters. Simultaneously Dr. Abbot observed at Bassour (1,160 m.) on this particular night, as well as during the following one, when I took measurements on the top of Mouzaia (1,610 m.). The result of these observations will be found among the investigations of the California expedition, one of the purposes of which was to consider more closely the problem of the influence of altitude upon the radiation of the atmosphere. For assistance with the practical arrangements in connection with the expedition to Mouzaia my hearty thanks are due to M. de Tonnac and M. Raymond, property owners.

As the most important result of the observations in Algeria it was found that the water vapor exerted a very marked influence upon the nocturnal radiation to the sky; a change in the water-vapor pressure from 12 to 4 mm., causing an increase in the nocturnal radiation amounting to about 35 per cent, other conditions being equal. From the observations it was possible to arrive at a logically founded mathematical expression for this influence.

A further investigation of the problem seemed, however, necessary. My special attention was directed to the influence of altitude and the influence of the temperature conditions of the instrument and of the atmosphere upon the radiation to the sky. For this purpose the climatic and geographic conditions of California were recommended as being suitable by Dr. Abbot.

There is probably no country in the world where such great differences in altitude are found so near one another as in California. Not far from Yosemite Valley, in the mountain range of Sierra Nevada, the highest peak in the United States, Mount Whitney, raises its ragged top to 4,420 meters, and from there one can look down into the lowest country in the world, the so-called Death Valley—200 meters below sea level. And further south, near the Mexican frontier, there is the desert of the Salton Sea, of which the lowest parts are below sea level; a desert guarded by mountain ranges whose highest peaks attain about 3,500 meters in altitude. In the summer the sky is almost always clear; a month and more may pass without a cloud being visible. It was evident that the geographical as well as the meteorological conditions of the country were very favorable for the investigations I contemplated.

On the advice of Dr. Abbot, I therefore drew up a detailed plan for an expedition to California, which was submitted to the Smithsonian Institution, together with an application for a grant from the Hodgkins Fund. The application was granted by the Institution, to whose distinguished secretary, Dr. Charles D. Walcott, I am much indebted for his great interest in the undertaking. The program for the expedition was as follows:

1. Preliminary observations at the top of Mount San Antonio (3,000 m.) and at Claremont (125 m.) simultaneously (3 nights).

2. Simultaneous observations at the top of Mount San Gorgonio (3,500 m.) and at Indio in the Salton Sea Desert (0 m.), (3 nights).

3. Expedition to Mount Whitney. Here the observations were to be extended to three stations at different altitudes, where simultaneous measurements should be made every clear night during a period of about two weeks. The stations proposed were: Lone Pine, at the foot of the mountain, at 1,200 m. altitude; the summit of Mount Whitney (4,420 m.); and an intermediate station on one of the lower ridges that project on the eastern side of the mountain. During this part of the expedition, as well as during the preliminary ones, the observations were to be made once an hour during the entire night, from 8 o'clock in the evening to 4 o'clock in the morn-

ing. It was proposed also to make pyrheliometric observations during the days on the top of Mount Whitney. These latter measurements, which are taken as a basis for determinations of the solar constant are given in an appendix written by Dr. Kennard and myself.[1]

The Mount Whitney part of the expedition was regarded as by far the most important, both on account of the higher altitude of the station, and because of the conveniences presented by the position on the top of the mountain, which made it possible to observe there during a considerable interval of time. Mount Whitney is too well known through the expedition of Langley (in 1881) and of Abbot (in 1909 and 1910) to need any description here. In the year 1909, the Smithsonian Institution erected—on the suggestion of Directors Campbell and Abbot—a small stone house on the summit as a shelter for future observers. Permission was given me by the Smithsonian Institution to use this shelter for the purposes of the expedition.

As the observations were to be made simultaneously in different places, several observers were needed. At this time (in the beginning of the year 1913) I was engaged in some investigations at the physical laboratory of Cornell University, Ithaca, N. Y., and from there I was enabled to secure the services of my friend, Dr. E. H. Kennard, as a companion and an able assistant in the work of the expedition. Further, Prof. F. P. Brackett, Director of the Astronomical Observatory of Pomona College, Claremont, California, promised his assistance, as also did Professor Williams and Mr. Brewster from the same college.

On the 8th of July, 1913, the author and Dr. Kennard arrived at Claremont, California, where Messrs. Brackett, Williams, and Brewster joined us. Through the kindness of Prof. Brackett the excellent little observatory of Pomona College was placed at my disposal as headquarters, and here the assistants were instructed, and the instruments—galvanometers, actinometers and ammeters—were tested.

On the 12th of July the first preliminary expedition was made, when the author and Mr. Brewster climbed to the summit of Mount San Antonio, the highest peak of the Sierra Madre Range (3,000 m.) and observed there during the two following nights. At the same time Prof. Brackett and Dr. Kennard observed at Claremont at the foot of the mountain, but unfortunately at the

[1] This paper has also appeared in the Astrophysical Journal, Vol. 39, No. 4, May, 1914.

lower station the sky was cloudy almost the entire time, which condition, however, furnished an opportunity to demonstrate the effect of dense homogeneous cloud banks upon the nocturnal radiation.

The first simultaneous observations at different altitudes, favored by a clear sky at both stations, were obtained during a subsequent expedition, also of a preliminary nature, when the author and Mr. Brewster, proceeded to Indio in the Salton Sea Desert, and Prof. Brackett, Prof. Williams, and Dr. Kennard succeeded in climbing Mount San Gorgonio (3,500 m.), the highest peak of the San Bernardino range. Indio was chosen because of its low altitude (0 m.) and because of its meteorological conditions, the sky being almost always clear in this part of the desert. The horizon was almost perfectly free, the San Bernardino and San Jacinto mountains rising only to about 10° above the horizon. The temperature at the lower station, which is situated in one of the hottest regions of America, reached, in the middle of the day, a point between 40° and 46° C.; in the night-time it fell slowly from about 30° in the evening to about 20° in the morning. Here some interesting observations were obtained, showing the influence of temperature upon radiation to the sky. At the same time, the other party made observations on the top of Mount San Gorgonio (3,500 m.) situated about 40 miles farther north. The party climbed to the top in a heavy snowstorm, and during the two following, perfectly clear, nights, observations were taken, the temperature at the top being about 0° C. Thus simultaneous observations were obtained on two places differing in altitude by 3,500 meters.

The expedition to Mount Whitney, for which preparations were made immediately after the return of the parties to Claremont, was regarded as the most important part of the field work. On the proposal of Director Abbot, the U. S. Weather Bureau had resolved to cooperate with my expedition in this part of the undertaking. Under the direction of Mr. Gregg and Mr. Hathaway of that Bureau, the upper air was to be explored by means of captive balloons, carrying self-recording meteorological instruments. In this way the temperature and the humidity would be ascertained up to about 1,500 meters above the point from which the balloons were sent up. The ascents were to be made from Lone Pine (by Mr. Hathaway) and from the summit of Mount Whitney (by Mr. Gregg). The latter ascents are probably the first that have been carried on by means of captive balloons at altitudes exceeding 4,000 meters.

On July 29 the party, accompanied by Mr. Gregg and Mr. Hathaway of the Weather Bureau, left Los Angeles for Lone Pine, Inyo County, California. After arrival there in the morning a suitable place was found for the lower station, and final arrangements were made for the guide and pack train for the mountain party. The disposition of the observers was to be Ångström and Kennard at the upper station, Brewster and an assistant at the intermediate station, where observations were to be made only in the mornings and evenings, and, finally, Williams and Brackett at the lower station.

On Thursday, July 31, the mountain party set out from Lone Pine with Elder, the Mexican guide, a cook, a pack train of seven mules, and a light cart to convey the party up the incline to the foot of Lone Pine Canyon, whence the ascent would have to be made on foot or in the saddle. After some prospecting on the way, the intermediate station was located on a crag overlooking the canyon from a precipitous height of several hundred feet. Here Brewster was stationed and was later joined by a Mexican helper. Leaving Brewster, the party climbed that night to Elder's camp, at an elevation of nearly 3,000 meters. In spite of a storm which began with rain in the night and changed to snow, increasing in severity the next day, the summit was reached early in the afternoon. A thrilling electric storm raged for some time. Every point of rock and the tips of the nails and hair emitted electric discharges. But the little stone-and-iron building of the Smithsonian Institution furnished shelter. That the climbing of the mountain, with many instruments and a large pack train, succeeded without an accident, is largely due to the excellent work of Mr. G. F. Marsh, of Lone Pine, who had worked for weeks with a gang of 20 men to open up the trail, so that the ascent might be possible for men and pack animals carrying provisions, instruments, and fuel. Even so, in its upper reaches the trail passes over long slopes of ice and snow and clings to the face of naked and rugged steeps, where a false step would be fatal.

On the top of the mountain, a short distance from the house, is a little flat-roofed stone shelter about six feet square and eight feet high. In and upon this shed most of the instruments were set up.

On the whole, the weather upon the mountain was very favorable for the work of the expedition. Observations were made on seven nights out of a possible ten. Besides the hourly records of nocturnal radiation, the solar radiation was measured at suitable intervals throughout the day, and complete records were kept of the temperature, humidity, and pressure of the air at the summit. Strong winds

interfered with the balloon ascents, but several of them were successful. During three nights records were obtained up to 400 to 1,000 meters above the station.

The observations at the lower stations have also proved to be very satisfactory. In the section on the experimental work the observations will be discussed in detail.

CHAPTER II

HISTORICAL SURVEY[1]

Insolation from the sun, on the one hand, and, on the other, radiation out to space, are the two principal factors that determine the temperature conditions of the earth, inclusive of the atmospheric envelope. If we do not consider the whole system, but only a volume element within the atmosphere (for instance, a part of the earth's surface) this element will gain heat: (I) through direct radiation from the sun; (II) from the portion of the solar radiation that is diffused by the atmosphere; (III) through the temperature radiation of the atmosphere. The element will lose heat through temperature radiation out to space, and it will lose or gain heat through convection and conduction. In addition to these processes, there will often occur the heat transference due to the change of state of water: evaporation, condensation, melting, and freezing. The temperature radiation from the element to space, diminished by the temperature radiation to it from the atmosphere, is often termed "nocturnal radiation," a name that is suggested by the fact that it has generally been observed at night, when the diffused skylight causes no complication. In this paper it will often be termed "effective radiation." The effective radiation out to the sky together with the processes of convection and conduction evidently under constant conditions must balance the incoming radiation from sun and sky. The problem of the radiation from earth to space is therefore comparable in importance to the insolation problem in determining the climatic conditions at a certain place.

The first observations relating to the problem of the earth's radiation to space are due to the investigations of Wilson,[2] Wells,[3] Six,[4] Pouillet,[5] and Melloni,[6] the observations having been made between the years 1780 and 1850. These observers have investigated the

[1] Large parts of this chapter as well as of chapters III, IV and V: 1 have appeared in the Astrophysical Journal, Vol. 37, No. 5, June, 1913.

[2] Edinburgh Phil. Trans., Vol. 1, p. 153.

[3] Ann. de chimie et de physique, tome 5, p. 183, 1817.

[4] Six, Posthumous Works, Canterbury, 1794.

[5] Pouillet, Elément de physique, p. 610, 1844.

[6] Ann. de chimie et de physique, ser. 3, tome 22, pp. 129, 467, 1848.
Ibid., ser. 3, tome 21, p. 145, 1848.

nocturnal cooling of bodies exposed to the sky, a cooling that is evidently not only due to radiation but is also influenced by conduction and convection of heat through the surrounding medium. Melloni, making experiments in a valley called La Lava, situated between Naples and Palermo, found that a blackened thermometer exposed on clear nights showed a considerably lower value (3.6° C.) than an unblackened one under the same conditions. Melloni draws from his experiments the conclusion that this cooling is for the most part due to the *radiation* of heat to space. In fact, such a cooling of exposed bodies below the temperature of their surroundings was very early observed. Natives of India use it for making ice by exposing flat plates of water, on which dry grass and branches are floating, to the night-sky. The formation of ice, due to nocturnal radiation, has been systematically studied by Christiansen.

So far the observations have been qualitative rather than quantitative and the object of the observations not clearly defined. The first attempt to measure *the nocturnal radiation* was made by Maurer, the Swiss meteorologist. In the year 1886, Maurer published a paper dealing with the cooling and radiation of the atmosphere.[1] From thermometrical observations of the atmosphere's cooling he deduces a value $\delta = 0.007.10^{-4}$ (cm.^{3} min.) for the radiation coefficient of the air and from this a value for the radiation of the whole atmosphere: $0.39 \dfrac{\text{cal.}}{\text{cm.}^2 \text{ min.}}$ at 0°. This value is obtained on the assumption that the atmosphere is homogeneous, having a height of 8.10^5 cm. and by the employment of the formula

$$R = \frac{S}{a}\left[1 - e^{-ah}\right]$$

where S is the radiation, a the absorption coefficient and $h = 8.10^5$. Maurer's manner of proceeding in obtaining this value can scarcely be regarded as quite free from objection, and in the theoretical part of this paper I shall recur to that subject. But through his theory Maurer was led to consider the problem of the nocturnal radiation and to measure it.[2] His instrument consisted of a circular copper disk, fastened horizontally in a vertical cylinder with double walls, between which was running water to keep the cylinder at a constant temperature. The cover of the cylinder was provided with a circular diaphragm, which could be opened or shut. Opening and shutting this diaphragm at certain intervals of time, Maurer could,

[1] Meteorologische Zeitschrift, 1887, p. 189.

[2] Sitzber. der Ak. der Wissensch. zu Berlin, 1887, p. 925.

from the temperature of the disk read on a thermometer, compute the radiation. He made his observations at Zürich during some clear nights in June and found a nocturnal radiation amounting to 0.13 cal. By this method, as well as by the similar method used by Pernter, certain corrections must be made for conduction and convection, and certain hypotheses must be made in order to compute the radiation to the whole sky from the radiation to a limited part of it given by the instrument.

The observations of Pernter[1] were made simultaneously on the top of Sonnblick (3,095 m.) and at Rauris (900 m.). He observed with an actinometer of the Violle type and found a radiation of 0.201 cal. (unless otherwise stated the radiation is always given as $\frac{\text{cal.}}{\text{cm.}^2 \text{ min.}}$ in this paper) at the higher station and 0.151 at the lower one.

Generally the methods for determining the effective radiation out to space have proceeded parallel—with a certain phase difference—with the development of the methods of pyrheliometry. In the year 1897, Homén[2] published an important paper bearing the title "Der tägliche Wärmeumsatz im Boden und die Wärmestrahlung zwischen Himmel und Erde." His method was an application of a method employed by K. Ångström for measuring sun radiation. The principal part of the instrument consists of two exactly equal copper plates. In the plates are introduced the junctions of a thermocouple. If now one of the plates is exposed to the radiation and the other covered, there will be a temperature difference between the disks growing with the time. If at a certain temperature difference, δ, the conditions are interchanged between the disks, they after a certain time, t, will get the same temperature. Then the intensity of the radiation is given by the simple formula:

$$Q = \frac{2W\delta}{t}$$

where W is the heat-capacity of the disks. By this method the effects of conduction and convection are eliminated. The weak point of the instrument, if applied to measurements of the nocturnal radiation, lies in the employment of a screen, which must itself radiate and cool, giving rise to a difference in the conditions of the two disks. Homén draws from his observations on the radiation between earth and sky the following conclusions:

[1] Sitzber. der Ak. der Wissensch. zu Wien, 1888, p. 1562.

[2] Homén, Der tägliche Wärmeumsatz, etc., Leipzig, 1897.

(1) If the sky is clear, there will always be a positive radiation from earth to sky, even in the middle of the day.

(2) If the sky is cloudy, there will always, in the daytime, be a radiation from sky to earth.

(3) In the night-time the radiation for a clear as well as for a cloudy sky always has the direction from earth to sky.

Homén also made some measurements of the radiation to different parts of the sky and found that this radiation decreases rapidly when the zenith angle approaches the value 90°. His values of the nocturnal radiation vary between 0.13 and 0.22 for a clear sky.

When relatively large quantities of heat are to be measured under circumstances where the conduction and convection are subject to considerable variation, it is favorable if one can apply a zero method, where the instrument is kept the whole time at the temperature of its surroundings. As the first attempt to discover such a method may be regarded the experiment of Christiansen, who measured the thickness of ice formed on metal disks that were placed on a water-surface and exposed to the sky. In 1899 K. Ångström published a description of the compensation pyrheliometer and shortly afterward (1903) a modified type of this instrument was used by Exner[1] in order to measure the nocturnal radiation on the top of Sonnblick. In agreement with former investigations made by Maurer and Homén, Exner found the radiation to be relatively constant during the night. He points out that there are tendencies to a slight maximum of radiation in the morning, one to two hours before sunrise. To the method of Exner it can be objected that the radiation is only measured for a part of the sky. In order to obtain the radiation to the whole sky, Exner applied a correction with regard to the distribution of radiation to the different zones given by Homén. It will be shown in a later part of this paper that such a procedure is not entirely reliable.

In 1905 K. Ångström[2] gave a description of an instrument specially constructed for measuring the nocturnal radiation. The instrument is founded upon the principle of electric compensation, and, as it has been used in the work here published, I shall in a following chapter give a more detailed consideration of it. With this instrument Ångström measured the nocturnal radiation during several nights at Upsala and found values varying between 0.13 and

[1] Met. Zt., 1903, p. 409.

[2] Nova Acta Reg. Soc., Sc. Upsal., Ser. 4, Vol. 1, No. 2.

0.18 cal. for a clear sky. With this type of instrument Lo Surdo[1] has made measurements at Naples. He observed the radiation during a clear and especially favorable night and found a pronounced maximum about two hours before sunrise. Contrary to Homén he finds a positive access of radiation from the sky even when the sky is clear. The following table gives a brief survey of the results obtained by different observers:

Observer	Date	Place	Temperature	Height	Mean Value
Maurer.....	June 13-18, 1887	Zürich	15°-18°	500	0.128
Pernter.....	Feb. 29, 1888	Sonnblick	—8°	3095	0.201
Pernter.....	Feb. 29, 1888	Rauris	......	900	0.151
Homén.....	Aug., 1896	Lojosee	......	....	0.17
Exner......	1902	Sonnblick	......	3106	0.19
Exner......	July 1, 1902	Sonnblick	......	3106	0.268 (max.)
K. Ångström	May-Nov., 1904	Upsala	0°-10°	200	0.155
Lo Surdo...	Sept. 5-6, 1908	Naples	20°-30°	30	0.182
A. Ångström	July 10-Sept. 10, 1912	Algeria	20°	1160	0.174

If we apply the constant of Kurlbaum $\sigma=7.68.10^{-11}$, to the law of Stefan-Boltzmann for the radiation of a black surface, we shall find that such a surface at 15° C. temperature ought to radiate 0.526 cal. If the observed effective radiation does not amount to more, for instance, than 0.15 cal., this must depend upon the fact that 0.376 cal. is radiated to the surface from some other source of radiation. In the case of the earth this other source of radiation is probably to a large extent its own atmosphere, and in the following pages we shall often for the sake of convenience discuss this incoming radiation as if it were due to the atmosphere, ignoring the fact that a small fraction of it is due to the stars and planetary bodies.

Then the source of variations in the effective radiation to the sky is a double one. The variations depend upon the state of the radiating surface and also upon the state of the atmosphere. And the state of the atmosphere is dependent upon its temperature, its composition, density, the partial and total pressure of the components, and upon the presence of clouds, smoke, and dust from various sources.

The present paper is an attempt to show how the effective radiation, and consequently also what we have defined as the radiation of the atmosphere, is dependent upon various conditions of the atmosphere. It must be acknowledged that the conditions of the atmosphere are generally known only at the place of observation.

[1] Nuovo Cimento, Ser. 5, Vol. 15, 1908.

But it has been shown by many elaborate investigations that, on an average, we are able, with a certain amount of accuracy, to draw conclusions about a large part of the atmosphere from observations on a limited part of it. This will be further discussed in a chapter on the distribution of water vapor and temperature conditions. The discussion of the observations will therefore be founded upon mean values, and will lead to a knowledge of average conditions.

CHAPTER III

A. THEORY OF THE RADIATION OF THE ATMOSPHERE

The outgoing effective radiation of a blackened body in the night must be regarded as the sum of several terms: (1) the radiation from the surface toward space (E_c) given, for a "black body," by Stefan's radiation law; (2) the radiation from the atmosphere to the surface (E_a), to which must be added the sum of the radiations from sidereal bodies (E_s), a radiation source that is indicated by Poisson by the term "sidereal heat." If J is the effective radiation, we shall evidently have:

$$J = E_c - E_a - E_s$$

For the special case where the temperature of the surface is constant and the same is assumed to be the case for the sidereal radiation, we can write:

$$J = K - E_a$$

K being a constant. Under these circumstances the variations in the effective radiation are dependent upon the atmospheric radiation only, and the problem is identical with the problem of the radiation from a gaseous body, which in this case is a mixture of several different components. As is well known from thorough investigations, a gaseous body has no continuous spectrum, but is characterized by a selective radiation that is relatively strong at certain points of the spectrum and often inappreciable at intermediate points. The law for the distribution of energy is generally very complicated and is different for different gases. The intensity is further dependent upon the thickness, density, and temperature of the radiating layer.

Let us consider the intensity of the radiation for a special wave length λ, from a uniform gaseous layer of a thickness R and a temperature T toward a small elementary surface $d\tau$. To begin with, we will consider only the radiation that comes in from an elementary radiation cone, perpendicular to $d\tau$, which at unit distance from $d\tau$ has a cross-section equal to $d\Omega$. One can easily deduce:

$$J_\lambda = \int_0^R \epsilon_\lambda e^{-a_\lambda r}\, dr d\Omega d\tau$$

which gives for unit surface:

$$J_\lambda = \frac{\epsilon_\lambda}{a_\lambda} \cdot d\Omega (1 - e^{-a_\lambda R}) \qquad (1)$$

where ϵ_λ is the emission coefficient and a_λ the absorption coefficient for the wave length λ.

Evidently:

$$\lim_{R=\infty} J_\lambda = \frac{\epsilon_\lambda}{a_\lambda} d\Omega = E_\lambda d\Omega \tag{2}$$

where E_λ is the radiation from a black body for the wave length λ at the temperature T. It follows from this that, in all cases where one can assume a_λ to be independent of the temperature, ϵ_λ must be the same function of the temperature as E_λ multiplied by a constant. That means that the radiation law of Planck must always hold, as long as the absorption is constant:

$$\epsilon_\lambda = C\lambda^{-5} \frac{1}{e^{\frac{c_1}{\lambda T}} - 1}$$

If now the gas has many selective absorption bands we may write instead of (1):

$$J = \Sigma E_\lambda (1 - e^{-a_\lambda R}) d\Omega \tag{3}$$

With the aid of (3) it is always possible to calculate the radiation for any temperature, if the absorption coefficient, which is assumed to be constant, is known.

If R is taken so great that the product $a_\lambda \cdot R$ has a very large value for all wave lengths, the expression (3) will become

$$\lim_{a_\lambda R=\infty} J = \Sigma E_\lambda = \sigma T^4 \tag{4}$$

which is Stefan's radiation law for a black body.

If $a_\lambda R$ cannot be regarded as infinitely great for all wave lengths, the radiation, J, will be a more complicated function of T expressed by the general relation (3). The less the difference is between the radiation from the gas and the radiation from a black body at the same temperature, so much more accurately will the formula (4) express the relation between radiation and temperature.

Dr. Trabert[1] draws from observations on the nocturnal cooling of the atmosphere the conclusion that the radiation from unit mass of air is simply proportional to the absolute temperature. If this should be true, it can be explained only through a great variation of a_λ for a variation in the temperature. Later Paschen[2] and Very[3] measured in the laboratory the radiation from air-layers at different

[1] Denkschriften der Wien. Akad., 59.

[2] Wied. Ann., 50, 1893.

[3] Very, Atmospheric Radiation, Washington, 1900.

temperatures and found a much more rapid increase with rising temperature than that indicated by Trabert.

From (3) we shall deduce some general laws for the radiation from gaseous layers. From such a layer the radiation will naturally come in from all sides, R being different for different angles of incidence. We may therefore write (3) in the form:

$$J = \sum^{\gamma}\sum^{\lambda} E_\lambda (1 - e^{-a_\lambda \cdot \gamma R}) \tag{5}$$

where γ is always a positive quantity. Now we have:

$$\frac{dJ}{dR} = \sum^{\gamma}\sum^{\lambda} E_\lambda a_\lambda \cdot \gamma \cdot e^{-a_\lambda \cdot \gamma R}$$

That is, we have the very evident result that the radiation of a gaseous layer increases with its thickness (or density). For very thick layers the increase is zero and the radiation constant.

By a second differentiation we get:

$$\frac{d^2J}{dR^2} = -\sum^{\gamma}\sum^{\lambda} (a_\lambda \cdot \gamma)^2 e^{-a_\lambda \cdot \gamma R}$$

The second derivative is always negative, which shows that *the curve giving the relation between radiation and thickness is always concave toward the R-axis.*

We may now go a step further and imagine that on the top of the first layer is a new layer, which radiates in a certain way different from that of the first layer. A part of the radiation from the second layer will pass the first layer without being absorbed. That part we denote by H. Another fraction of the radiation will be absorbed, and it will be absorbed exactly at the wave lengths where the first layer is itself radiating. The sum of the radiations from the two layers can therefore be expressed by a generalization of (5)

$$\bar{J} = H + \sum^{\gamma}\sum^{\lambda} [E_\lambda - (E_\lambda - E'_\lambda) e^{-a_\lambda \cdot \gamma R}] \tag{6}$$

where E'_λ is the radiation from the second layer at the wave length λ. If this layer has the same or a lower temperature than the first one, we evidently have:

$$E'_\lambda \leqq E_\lambda$$

In that case the laws given above in regard to the derivatives of J evidently hold, and we find here also that *the less the thickness of the layer is, so much more rapid is the increase of radiating power with increase in thickness.* This is true for a combination of several layers under the condition that the temperature is constant or is a decreasing function of the distance from the surface to which the

radiation is measured. We shall make use of that fact in the experimental part of this paper, in order to calculate the maximum value of the radiation of the atmosphere when the density of one of its components approaches zero.

The relation

$$J = \Sigma E_\lambda (1 - e^{-a_\lambda \cdot R}) d\Omega$$

represents the general expression for the radiation within the radiation cone $d\Omega$ perpendicular to the unit of surface. Maurer bases his computation of the atmosphere's radiation upon the more simple expression

$$J = \frac{\epsilon}{a}(1 - e^{-aR})$$

where he puts R equal to the height of the reduced atmosphere and a equal to the absorption coefficient of unit volume. This is evidently an approximation that is open to criticism. In the first place it is not permissible to regard R as the height of the reduced atmosphere, and this for two reasons: first, because the radiation is chiefly due to the existence of water vapor and carbon dioxide in the atmosphere vapors, whose density decreases rapidly with increase in the altitude; and, secondly, because we have here to deal with a radiation that enters from all sides, R being variable with the zenith angle. But even if we assign to R a mean value with regard to these conditions, Maurer's formula will be true only for the case of one single emission band and is, for more complicated cases, incapable of representing the real conditions. I have referred to this case because it shows how extremely complicated are the conditions when all are taken into consideration.

If, with Maurer, we regard the atmosphere as homogeneous and of uniform temperature, having a certain height, h, we must, considering that R is a function of the zenith angle, write (1) in the following form:

$$J_\lambda = \frac{\epsilon_\lambda}{a_\lambda} \int d\Omega \left(1 - e^{-a_\lambda \cdot \frac{h}{\cos \Phi}}\right) \cos \Phi \qquad (7)$$

where the integration is to be taken over the hemisphere representing the space. Now we have

$$d\Omega = d\Phi d\psi \sin \Phi$$

and therefore

$$J_\lambda = \frac{\epsilon_\lambda}{a_\lambda} \int_0^{2\pi} d\psi \int_0^{\frac{\pi}{2}} \left(1 - e^{-a_\lambda \cdot \frac{h}{\cos \Phi}}\right) \sin \Phi \cos \Phi \, d\Phi \qquad (8)$$

This expression can easily be transformed into:

$$J_\lambda = \pi E_\lambda \left(1 - 2\rho^2 \int_\rho^\infty \frac{e^{-x}}{x^3}\, dx \right) \tag{9}$$

where $\rho = a_\lambda \cdot h$ and $x = a_\lambda \cdot \frac{h}{\cos \Phi}$. When $h \doteq 0$, this expression approaches zero; when $h \doteq \infty$, J_λ approaches the value πE_λ, which is equal to the radiation of a black body under the same conditions. We have, in fact:

$$\lim_{\rho=\infty} \rho^2 \int_\rho^\infty \frac{c^{-x}}{x^3}\, dx = \lim_{\rho=\infty} \frac{\frac{c^{-\rho}}{\rho^3}}{\frac{1}{2} \cdot \frac{1}{\rho^3}} = \lim_{\rho=\infty} \frac{c^{-\rho}}{2} = 0$$

and in a similar way:

$$\lim_{\rho=0} \rho^2 \int_\rho^\infty \frac{c^{-x}}{x^3}\, dx = \frac{1}{2}$$

We shall now consider in what respects these relations are likely to be true for the very complicated conditions prevailing in the atmosphere. The atmosphere, considered in regard to its radiating properties, consists of a *low radiating layer* up to about 10 km. made up of water vapor and carbon dioxide, and a *higher radiating layer* composed of carbon dioxide and ozone. These two layers naturally merge into one another, but it is convenient here to suppose a clear distinction, our surface of separation being at the altitude where the water vapor ceases to have any appreciable influence upon the radiation of the atmosphere.

The radiation of the lower layer is chiefly dependent upon the amount of water vapor contained in it, the strong radiation of the carbon dioxide being at wave lengths where the water vapor itself must radiate almost in the same way as a black body. At any rate, the *variations of the radiation* in that part of the atmosphere must depend almost entirely on the variations in the water-vapor element, the carbon-dioxide element being almost constant, as well in regard to time, as to place and to altitude. The probable slight influence of variations in the amount of ozone contained in the upper strata of the atmosphere, we may at present ignore. Including the constant radiation of the carbon dioxide in the radiation of the upper layer, we can apply the expression (5) and arrive at

$$J = H + \sum^{\gamma}\sum^{\lambda} [E_\lambda - (E_\lambda - E'_\lambda) e^{-a_\lambda \cdot \gamma R}] \tag{10}$$

where R can be put equal to the height of the reduced water-

vapor atmosphere, or, what is the same, the amount of water vapor contained in a vertical cylinder of 1 cm.^{2} cross-section. Here a_λ has been considered as a constant. As has been shown by Miss von Bahr, the law of Beer does not, however, hold for vapors, absorption being variable with the total pressure to which the vapor is subjected. As will be seen in the experimental part of the paper, this circumstance has probably introduced a slight deviation from the conditions to be expected from the assumption of a constant value for a.

From (10) we draw a similar conclusion to the preceding: *with decreasing water-vapor content, the radiation of the atmosphere will also decrease and this decrease will be more rapid at a low water-vapor content than at a high one.*

The simplest form in which (10) can be written is obtained from the assumption that we can put:

$$H+\overset{\gamma\lambda}{\Sigma\Sigma}E_\lambda=K$$

and

$$\overset{\gamma\,\lambda}{\Sigma\Sigma}(E_\lambda-E'_\lambda)e^{-a_\lambda\gamma R}=Ce^{-a_m\gamma_m R}=Ce^{-\beta P}$$

where P is the height of the reduced water-vapor atmosphere. In such a case we shall obtain for the radiation of the atmosphere:

$$E_a=K-Ce^{-\beta P} \tag{11}$$

and for the effective radiation:

$$J=E'+Ce^{-\beta P} \tag{12}$$

We have heretofore supposed that the temperature of the radiating layer is constant. If that is not the case, it will introduce a new cause of variations. For every special wave length the radiation law of Planck will hold, but the integration will generally give a result different from the law of Stefan, dependent upon the different intensities of the various wave lengths relative to those of a black body. From the measurements of Rubens and Aschkinass on the transmission it can be seen, as will be shown later, that the radiation of the water vapor is very nearly proportional to the fourth power of the temperature, and as an approximation one may write:

$$E_a=\sigma T^4F(P)$$

or for the simple case (11):

$$E_a=cT^4(K''-e^{-\beta P})$$

Use will be made of these considerations in the treatment of the observations made.

B. DISTRIBUTION OF WATER VAPOR IN THE ATMOSPHERE[1]

In applying observations of the effective radiation toward the sky to determine a relation between the radiation of the atmosphere and its temperature and humidity, we are met by two great difficulties: First, the measurement of the total quantity of water contained in the atmosphere (I shall call this quantity hereafter the "integral water vapor" of the atmosphere); second, the determination of the effective atmospheric temperature.

There have been several elaborate investigations made of the water component of the atmosphere, by humidity measurements from balloons and on mountains, and indirectly by observations of the absorption, resulting from the water vapor, in the sun's radiation. Hann[2] has given the following formula, applicable to mountains, by which the water-vapor pressure at any altitude can be expressed as a function of the water-vapor pressure e observed at the ground. If e_0 is the observed water-vapor pressure in millimeters of mercury at a certain place, and h the altitude in meters above this place, the vapor pressure e_h at the height h meters is

$$e_h = e_0 e^{-\frac{h}{2730}} \qquad (1)$$

In the free air the decrease of the pressure with altitude is more rapid, especially at high altitudes. From observations in balloons, Süring has given the formula:[3]

$$e_h = e_0 e^{-\frac{h}{2606}\left(1+\frac{h}{20}\right)} \qquad (2)$$

If the atmosphere has the same temperature all through, the water element contained in a unit volume will be proportional to the vapor pressure. It is easy to see from the expression of Hann or of Süring that in such a case the integral water vapor will be proportional to the vapor pressure at the earth's surface. Through integration we shall get from Hann's formula:

$$F = 2.73 f_0 \cdot 10^3 \qquad (3)$$

and from Süring's formula:

$$F = 2.13 f_0 \cdot 10^3 \qquad (4)$$

where f_0 is the water content in grams per $cm.^3$ at the earth's surface.

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[1] See the concluding part of the preface. The discussion here given is for the purpose of indicating how far observations of humidity and temperature at the earth's surface may take the place of detailed information obtainable only by balloon flights in the study of atmospheric radiation.

[2] Hann, Meteorologie, pp. 224-226.

[3] Arrhenius, Lehrbuch der Kosmischen Physik, p. 624.

When one wishes to compute the integral water vapor from the pressure, the fall of temperature will cause a complication. From (1) we get, instead of (3):

$$T_h \cdot f_h = T_0 f_0 e^{-\frac{h}{2730}}$$

where T_h denotes the absolute temperature at the altitude h meters. T_h is a function of the altitude. This function differs from time to time and can be known only by balloon observations, but for present purposes we may use an approximate formula for T_h. We may write, T_h is equal to T_0 when $h=0$ and T_h is equal to 0^0 at $h=\infty$. Also, we must have $\frac{dT}{dh}=0$ at $h=\infty$. Accordingly (as the temperature influence in the formula is not great) it may suffice to assume that *T on an average* can be expressed by an exponential function of the form:

$$T_h = T_0 e^{-ah} \tag{6}$$

where a is to be determined by assuming that for $h=0$ $\frac{dT}{dh}$ is equal to the observed fall of temperature at the surface of the earth. For a fall of temperature of 0.7 degree per 100 m. one finds $a=0.03$. Introducing (3) into (1) we obtain the slightly different result for the integral water vapor:

$$F = 2.94 \cdot f_0 \cdot 10^3$$

and in a similar way from Süring's formula:

$$F = 2.30 \cdot f_0 \cdot 10^3$$

Hann's formula, which holds for mountain regions, indicates that here the element of water vapor contained in the atmosphere above a certain place is the absolute humidity at that place multiplied by a constant, the constant being independent of the altitude. This is not the case for the free air, if Süring's formula may be taken as a true expression of the conditions here prevailing. It is true that at a certain place we shall have $F=cf_0$, c being a constant, but this constant will differ at different altitudes. At an altitude of 4,400 m., we shall have

$$F = 1.8 \cdot f_{4{,}400} \quad \text{(free air)}$$

Fowle has made an interesting study of the absorption produced by water vapor in the sun's energy spectrum at Mount Wilson.[1] He also finds that the amount of water vapor contained in

[1] Astrop. J., 37, N. 5, p. 359.

the air is proportional to f_0 under average conditions. Individual observations deviate, however, greatly from the computed value, which is to be expected in view of the variety of atmospheric conditions.

Briefly it may be said that the observations agree in showing that on an average the integral water vapor above a certain place is proportional to the absolute humidity at that place. The factor of proportionality is, however, in general a function of the altitude.

The application of these results to the present question means that we can replace the water content of the whole atmosphere (P) by the absolute humidity at the place of observation multiplied by a constant, the latter being a quantity it is possible to observe.

For the general case we thus obtain

$$E_a = \overset{\gamma}{\Sigma}(1 - e^{-\gamma f_0}) + H$$

or for the simplest possible case

$$E_a = K - Ce^{-\gamma f_0}$$

More difficult is the problem of assigning a mean value for the temperature of the radiating atmosphere. It is evident that this temperature is lower than the temperature at the place of observation, and it is evident that it must be a function of the radiating power of the atmosphere. The most logical way to solve the problem would be to write T as a function of the altitude and apply Planck's law to every single wave length. The radiation of the atmosphere would thus be obtained as a function of the humidity and the temperature; but even after many approximations the expression would be very complicated and difficult to test. The practical side of the question is to find out through observations how the radiation depends upon the *temperature at the place of observation.* Suppose this temperature to be T_0. We may consider a number of layers parallel with the surface of the earth, whose temperatures are T_1, T_2, T_3, etc. Suppose, that these layers radiate as the same function cT_n^a of the temperature. Let us write: $T_1 = mT_0$; $T_2 = nT_0$; $T_3 = qT_0$. Then the radiation of all the layers will be:

$$J = cT_0^a \cdot [\alpha m^a + \beta n^a + \gamma q^a \ldots.]$$

at another temperature t_0 the radiation will be:

$$i = ct_0^a \cdot [\alpha m_1^a + \beta n_1^a + \gamma q_1^a \ldots.]$$

The condition that the whole layer shall radiate proportionally to this function cT_0^a, is evidently that we have:

$$m = m_1 ; n = n_1 ; q = q_1 \ldots .$$

that is: *The temperature at every altitude ought to be proportional to the temperature at the zero surface.* This is approximately true for the atmosphere. In the above consideration of the question, the emissive powers, α, β, $\gamma \ldots .$, are assumed to be independent of temperature.

The discussion explains how it is to be expected that from the temperature at the earth's surface we can hope to draw conclusions about the temperature radiation of the whole atmosphere.

CHAPTER IV

A. INSTRUMENTS

For the following observations I used one or more nocturnal compensation instruments, *pyrgeometers* of the type described by K. Ångström in a paper in 1905.[1] Without going into details, for which I refer to the original paper, it may be of advantage to give here a short description of the instrument.

Founded on the same principle of electric compensation used in the Ångström pyrheliometer, the instrument has the general form indicated in figure 2. There are four thin manganine strips (M), of which two are blackened with platinum black, the other two gilded. On the backs of the metal strips are fastened the two contact points of a thermojunction, connected with a sensitive galvanometer G. If the strips are shaded by a screen of uniform temperature, the thermojunctions will have the same temperature, and we may read a certain zero position on the galvanometer. If the screen is removed and the strips are exposed to the sky, a radiation will take place, which is stronger for the black strips than for the bright ones, and there will be a deflection on the galvanometer due to the temperature difference between the strips. In order to regain the zero position of the galvanometer, we may restore the heat lost through radiation by sending an electric current through the black strips. Theoretical considerations, as well as experiments made, show that the radiation is proportional to the square of the current used, that is,

$$R = ki^2$$

where k is a constant that depends upon the dimensions, resistance, and radiating power of the strips. As the radiating power from the strips is difficult to compute, the constant k is determined from experiment with a known radiation. The strips are exposed to radiate to a black hemisphere of known temperature T_1, and the constant is determined by the relation:

$$ki^2 = \sigma(T^4 - T_1^4)$$

where T is the temperature of the strips. The advantage of this construction over the form used for instance by Exner and Homén, where the effects of conduction and convection are also eliminated,

[1] Nova Acta Reg. Soc., Sc. Upsal., Ser. 4, Vol. 1, No. 2.

lies in the possibility of measuring the radiation to the whole sky and not only to a part of it, which is the case when one of the strips must be shaded. It must always be regarded as a dangerous approxi-

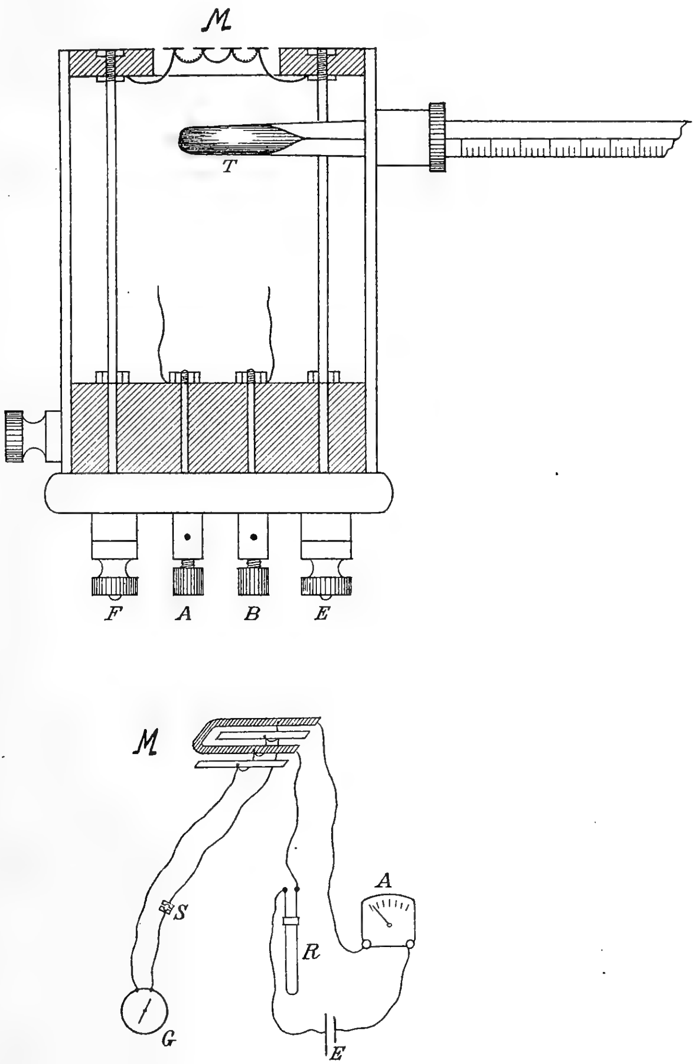

FIG. 2.—The Pyrgeometer.

mation to compute the radiation to the whole sky from the radiation to a fraction of it, assuming a certain standard distribution of radiation to the different zones of the sky. The method of adding up

different portions is too inconvenient and fails when the radiation is rapidly changing.

On the other hand, the value k is here dependent on the accuracy with which the radiation constant σ is determined. Further, since the emissive power of the strips, which is different for different wave lengths, enters into the constant k, this constant can be applied only for cases where the radiation is approximately of the same wave length as in the experiment from which k is computed. In the night-time this may be considered the case, the emissive power being the same for all heat waves longer than about 2 μ. But the instrument cannot, without further adjustment, be used for determining the radiation during the day, when the diffused radiation from the sky of short wave length enters as an important factor.

The constants of my three instruments, of which No. 17 and No. 18 were used at Bassour and California, and No. 22 in California, have been determined at the Physical Institute of Upsala on two occasions, before the expeditions by Dr. Lindholm of that Institute and after the expeditions by myself. The two determinations of the constants differ from one another only within the limits of probable error.

No.	Before	After	Mean
17	10.4	10.4	10.4
18	11.1	10.7	10.9
22	11.6	11.8	11.7

For the computations from the Algeria values the first values of the constants (for 17 and 18) have been used, for the California observations a mean value between them both. For the determination of the constants, Kurlbaum's value for σ has been used

$$\sigma = 7.68 \cdot 10^{-11}$$

not so much because this value is at present the most probable perhaps, as in order that observations with these instruments may be directly comparable with those of older ones. At any rate the relative values of the radiation must still be looked upon as the most important question.

The galvanometers that I have used were of the d'Arsonval type. They were perfectly aperiodic, and had a resistance of about 25 Ω and a sensitiveness of about $2 \cdot 10^{-8}$ amp. per mm. at meter distance. They generally showed a deflection of between 30 and 70 mm., when the strips were exposed to a clear sky. The galvanometers and the pyrgeometers were made by G. Rose, Upsala.

In the use of the compensation instrument one has to be careful that the instrument has had time to take the temperature of the

surroundings before measurements are made. If the instrument is brought from a room out into the open air, one can be perfectly safe after ten minutes exposure. When measurements are made on the tops of mountains or at other places where the wind is liable to be strong, I have found it advantageous to place the galvanometer as near the ground as possible. By reading in a reclining posture one can very well employ the instrument box itself for the galvanometer support. Some heavy stones placed upon, at the sides, and at the back of the box will keep the whole arrangement as steady as in a good laboratory, even when the wind is blowing hard.

For the measurements of the current used for compensation milliammeters from Siemens and Halske were employed.

The measurements of the humidity, as well as of the temperature, were carried out with aid of sling psychrometers made by Green of Brooklyn. The thermometers were tested for zero, and agreed perfectly with one another.

In order to compute the humidity from the readings of the wet and dry thermometers I have used the tables given by Fowle in the Fifth Revised Edition of the "Smithsonian Physical Tables" 1910.[1]

B. ERRORS

The systematic error to which the constants of all the electric pyrgeometers are subject has already been discussed. There are however some sources of accidental errors in the observations, and I shall mention them briefly. The observer at the galvanometer will sometimes find—especially if there are strong and sudden wind gusts blowing upon the instrument—that the galvanometer does not keep quite steady at zero, but swings out from the zero position, to which it has been brought by compensation, and returns to it after some seconds. The reason for this is probably that the two strips are not quite at the temperature of the surroundings. From measurements on the reflection of gold, it appears that the bright strip must radiate about 3 per cent of the radiation of a black body, consequently it will remain at a temperature slightly lower than that of the surroundings, which will sometimes cause a slight disturbance due to convection, the convection being not perfectly equal for the two strips. Another cause of the same effect is the fact that the strips are covered

[1] These tables are calculated from the formula

$$p = p_1 - 0.00066B\ (t - t_1)\ (1 + 0.00115t_1)$$

(Ferrel, Annual Report, U. S. Chief Signal Officer, 1886, App., 24).

by a diaphragm to about 1 mm. from the edges. On this part of its length the black strip will be heated but will not radiate, and the edges will therefore be slightly above the temperature of the surroundings. As I have made a detailed study of these edge-effects in the case of the pyrheliometer,[1] where I found that they affected the result only to about 1 per cent, I will not dwell upon them here. In the case of the pyrgeometer, the influence will result only in an unsteadiness of the zero, due to convection currents. The two mentioned effects will probably affect the result to not more than about ± 2 per cent, even under unfavorable conditions.

Much larger are the accidental errors in the measurements of the humidity. The ventilated psychrometer, used in these measurements, has been subjected to several investigations and critical discussions and it is therefore unnecessary to go into details. It will be enough to state that the results are probably correct to within 5 per cent for temperatures above zero, and to within about 10 per cent for temperatures below 0°.

[1] Met. Zeit., 8, 1914, p. 369.

CHAPTER V

1. OBSERVATIONS AT BASSOUR

The observations given in tables I and II were made at Bassour, Algeria, during the period July 10-September 10, 1912, at a height of 1,160 m. above sea level. In regard to the general meteorological and geographical conditions reference may be made to the introductory chapter. Every observation was taken under a perfectly cloudless sky, which in general appeared perfectly uniform. In regard to the uniformity of the sky, I may refer to chapter VI, where some observations are given that can be regarded as a test of the uniformity of the conditions.

TABLE I

Date	Time	B	Temperature	Δt	p	R
July 10	7:40	664.4	19.1	...	3.86	0.191
11	7:40	663.6	24.1	...	9.42	0.156
12	7:45	662.9	25.4	...	6.60	0.171
18	8:30	663.1	20.1	1.8	9.32	0.166
19	8:10	662.6	23.3	6.3	8.54	0.163
20	8:00	661.9	21.5	6.4	7.08	0.166
22	9:30	664.0	17.2	0.6	5.66	0.211
23	9:35	663.5	20.0	5.6	7.80	0.169
24	8:25	.....	19.5	5.7	8.36	0.159
25	8:35	664.9	18.8	—0.5	8.25	0.138
29	8:35	665.1	18.0	1.8	9.16	0.139
30	10:25	666.7	21.0	3.4	7.14	0.187
31	8:35	664.7	22.6	...	4.14	0.169
Aug. 1	9:45	662.3	23.8	4.2	4.40	0.201
2	8:55	662.9	20.3	2.4	7.54	0.171
3	9:05	.....	24.2	...	8.96	0.173
4	8:50	663.5	21.2	3.2	6.60	0.175
5	7:55	663.2	21.4	3.7	9.88	0.162
6	8:50	.....	23.6	3.3	5.89	0.173
10	8:50	665.7	25.0	3.3	9.98	0.178
11	8:20	666.9	22.8	2.7	10.20	0.158
13	9:00	662.7	19.5	1.5	8.86	0.171
14	10:00	662.6	18.6	0.0	11.90	0.147
15	8:30	665.4	20.6	—1.4	8.61	0.179
20	10:10	667.7	18.9	1.7	13.24	0.145
21	8:00	669.8	20.8	4.6	6.45	0.201
22	8:40	667.9	17.9	2.7	7.44	0.173
23	9:00	665.7	20.8	0.5	3.84	0.192
24	8:45	663.4	22.0	3.2	5.46	0.175
26	8:45	.....	21.5	...	3.80	0.217
27	9:05	.....	21.5	...	8.48	0.188
29	8:50	665.1	24.4	...	8.36	0.190
30	9:15	665.6	20.3	4.4	7.10	0.157
Sept. 3	8:35	664.3	13.8	4.2	10.40	0.138
4	8:05	666.7	11.1	...	4.98	0.169
5	9:50	664.0	20.8	2.1	4.57	0.205
6	9:30	661.5	20.0	2.4	3.99	0.220
8	9:00	666.7	15.7	—1.0	6.80	0.177

In table I are given: The date, the time of day, the barometric pressure B, the temperature of the air, the humidity (in mm. Hg.) ρ, and the effective radiation R. The temperature fall between the time of observation in the evening and the time of sunrise is indicated by Δt.

TABLE II

ρ	3.50–4.50			4.50–5.50			5.50–6.50		
	t	ρ	R	t	ρ	R	t	ρ	R
	19.1	3.86	0.191	22.0	5.46	0.175	17.2	5.66	0.211
	22.6	4.14	0.169	11.1	4.98	0.169	23.6	5.89	0.173
	23.8	4.40	0.201	20.8	4.57	0.205	20.8	6.45	0.201
	20.8	3.84	0.192	....	....	....	....	....	....
	21.5	3.80	0.217	....	....	....	....	....	....
	20.0	3.99	0.220	....	....	....	....	....	....
Means........	21.3	4.00	0.198	18.0	5.00	0.183	20.5	6.00	0.195

ρ	6.50–7.50			7.50–8.50			8.50–9.50		
	t	ρ	R	t	ρ	R	t	ρ	R
	25.4	6.60	0.171	20.0	7.80	0.169	24.1	9.42	0.156
	21.5	7.08	0.166	19.5	8.36	0.159	20.1	9.32	0.166
	21.0	7.14	0.187	18.8	8.25	0.138	23.3	8.54	0.163
	21.2	6.60	0.175	20.3	7.54	0.171	18.0	9.16	0.139
	17.9	7.44	0.173	21.5	8.48	0.188	24.2	8.96	0.173
	20.3	7.10	0.157	24.4	8.36	0.190	19.5	8.86	0.171
	15.7	6.80	0.177	....	....	....	20.6	8.61	0.179
Means........	20.4	6.98	0.173	20.7	8.13	0.169	21.4	8.98	0.164

ρ	9.50–10.50			11.90–13.24					
	t	ρ	R	t	ρ	R			
	21.4	9.88	0.162	18.6	11.90	0.147	....	....	....
	25.0	9.98	0.178	18.9	13.24	0.145	....	....	....
	22.8	10.20	0.158	....	....	....	....	....	....
	13.8	10.40	0.138	....	....	....	....	....	....
Means........	20.8	10.12	0.159	18.8	12.57	0.146	....	....	....

From figures 1a and 1b, where the radiation (crosses) and the humidity (circles) are given as functions of time, it is already evi-

dent that there must be a very close relationship between the two functions. In the figures the humidity values are plotted in the opposite direction to the radiation values. Plotting in this way we find that the maxima in the one curve correspond to the maxima in the other and minima to minima, which shows that low humidity and high effective radiation correspond and vice versa.

The observations of table I are now arranged in table II in such a way that all the radiation values that correspond to a water-vapor pressure falling between two given limits, are combined with one another in a special column. The mean values of humidity and radiation are calculated and plotted in a curve *aa,* figure 3, which gives the probable relation between water-vapor pressure and radiation. Tables I and II show that the temperature of the air, and consequently also that of the radiating surface, were almost constant for the different series and ought not, therefore, to have had any influence upon the form of the curve.

The smooth curve of figure 3 gives the relation between *effective radiation* and humidity. If we wish to know instead the relation between what we have defined as the radiation of the atmosphere and the humidity, we must subtract the value of the effective radiation from that of the radiation of a black body at a temperature of 20°. The curve indicates the fact, *that an increase in the water content of the atmosphere increases its radiation* and that *this increase will be slower with increasing vapor pressure.* It has been pointed out in the theoretical part that this is to be expected from the conditions of the atmosphere and from the laws of radiation. The relation between effective radiation and humidity can further be expressed by an exponential formula of the form:

$$R=0.109+0.134 \cdot e^{-0.10p}$$

or

$$R=0.109+0.134 \cdot 10^{(0.957-1)} \cdot$$

For the radiation of the atmosphere we get

$$E_a=0.453-0.134 \cdot c^{-0.10p}$$

That the radiation of the atmosphere, as a function of the water-vapor pressure, can be given in this simple form is naturally due to the fact that several of the radiation terms given through the general expression (3), chapter III, have already reached their limiting values for relatively low values of the water-vapor density. These terms, therefore, appear practically as constants and are in the empirical expression included in the constant term.

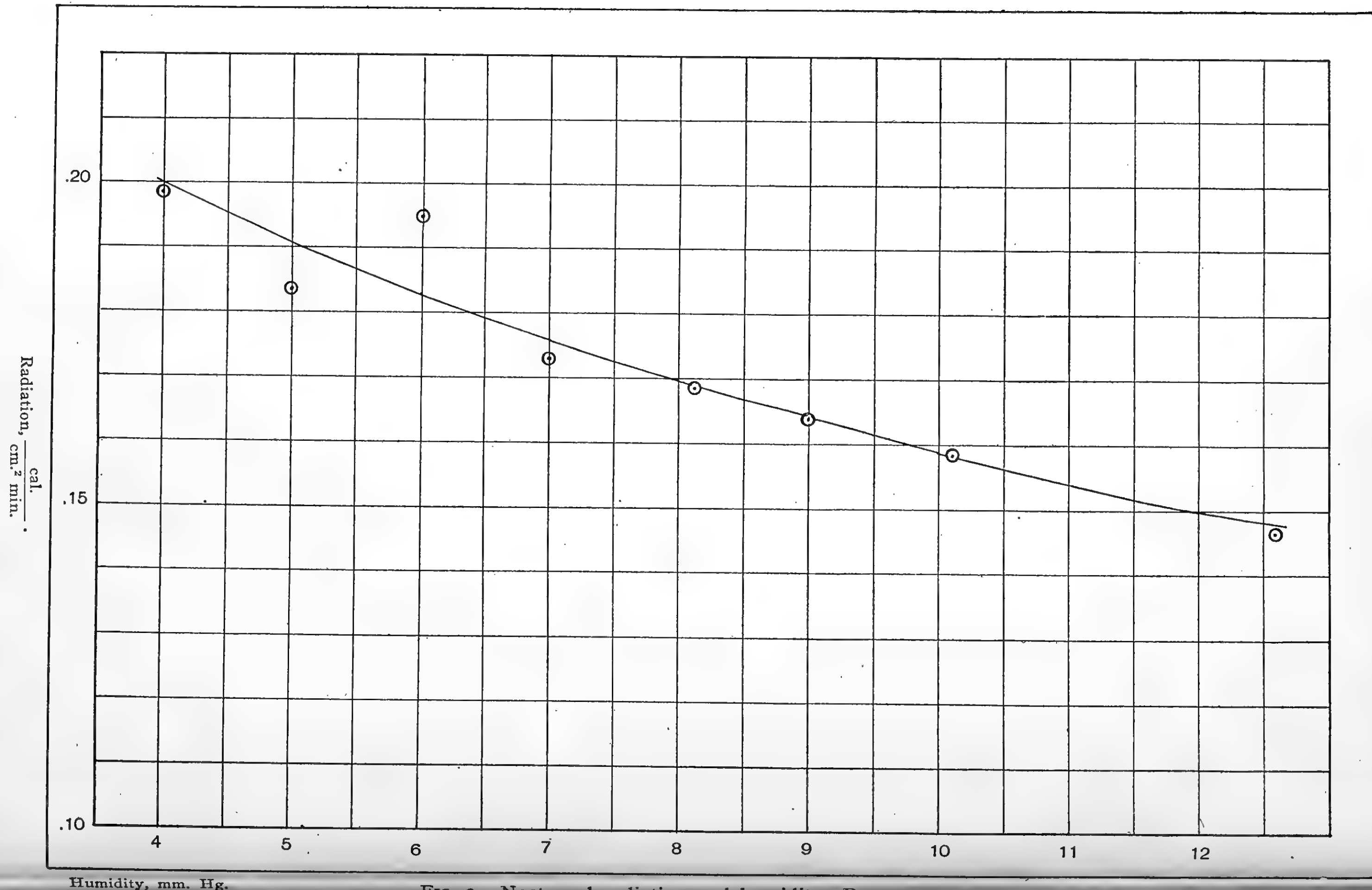

FIG. 3.—Nocturnal radiation and humidity. Bassour, 1912.

It is therefore evident that our formula can satisfy the conditions only between the limits within which the observations are made, and that in particular an extrapolation below 4 mm. water-vapor pressure is not admissible without further investigations. These conditions will be more closely considered in connection with the observations made on Mount Whitney, where the absolute humidity reached very low values.

For the case where ρ approaches very high values, the formula seems to indicate that the radiation approaches a value of about 0.11 cal., which may show that the water vapor, even in very thick layers, is *almost* perfectly transparent for certain wave lengths. This is probably only approximately true, and the apparent transparency would probably vanish totally if we could produce vapor layers great enough in density or thickness. In a subsequent chapter I shall discuss some observations that indicate that this is the case, and also that the formula given above must prove inadmissible for very great densities.

2. RESULTS OF THE CALIFORNIA EXPEDITION

The observations were taken simultaneously at different altitudes: (a) At Claremont (125 m.) and on the top of Mount San Antonio (3,000 m.); (b) at Indio in the Salton Sea Desert (0 m.) and on the top of Mount San Gorgonio (3,500 m.); and (c) at Lone Pine (1,150 m.), at Lone Pine Canyon (2,500 m.) and on the summit of Mount Whitney (4,420 m.).

A. INFLUENCE OF TEMPERATURE UPON ATMOSPHERIC RADIATION

Among the observations taken by this expedition I will first discuss some observations at Indio and Lone Pine separately, because they indicate in a very marked and evident way the effect upon the radiation of a very important variable, the temperature. The Indio observations of the effective radiation are given in table III and are graphically plotted in figures 17 and 18, where the radiation and the temperature during the night are plotted as functions of time. As will be seen from the tables, the humidity varied very little during these two nights.

As long as the temperature during the night is constant or almost constant, which is the case in mountain regions and at places near the sea, the effective radiation to the sky will not vary much, a fact that has been pointed out by several observers: Pernter, Exner, Homén, and others. But as soon as we have to deal with climatic conditions favorable for large temperature variations, the effective

radiation to the sky must be subject to considerable changes also. Such conditions are generally characteristic of inland climates and are very marked in desert regions, where the humidity is low and the balancing influence of the neighborhood of the sea is absent. Indio is situated in a desert region. In the middle of the day the temperature reached a maximum value of 43° C. on the 23d and 46° C. on the 24th of July. In the evenings at about 8 o'clock the temperature was down to 30° C., falling continuously to values of 21° and 19° C., respectively, in the mornings at 4:30, when the observations ceased. From the curves it is obvious that there is a close relation between the radiation and the temperature. Every variation in the temperature conditions is accompanied by a similar change in the radiation. In fact *a decrease in the temperature of the surrounding air causes a decrease in the effective radiation to the sky.* This is even more obvious from the observations taken at Lone Pine on August 5 and August 10, when very irregular temperature variations took place during the nights. The humidity conditions appeared almost constant. From the curves (figs. 19 to 21) can be seen how a change in the one function is almost invariably attended by a change in the other.

In regard to the radiating surfaces of the instrument, one is pretty safe in assuming that the total radiation is proportional to the fourth power of the temperature, an assumption that is based upon the constancy of the reflective power of gold and of the absorption power of platinum-black soot within the critical interval. The radiation of these surfaces ought, therefore, to follow the Stefan-Boltzmann law of radiation. For the radiation of the atmosphere we thus get:

$$E_{at} = E_{st} - R_t$$

Knowing E_{st} and R_t, of which the first quantity is given by the radiation law of Stefan, to which I have here applied the constant of Kurlbaum ($\sigma = 7.68 \cdot 10^{-11}$), and the second quantity is the effective radiation measured, I can calculate the radiation of the atmosphere. We are led to try whether this radiation can be given as a function of temperature by an expression

$$E_{at} = C \cdot T^a \tag{1}$$

similar in form to the Stefan-Boltzmann formula, and in which a is an exponent to be determined from the observations. From (1) we obtain:

$$\log E_{at} = \log C + a \log T$$

Now the observations of every night give us a series of corresponding values of E_{at} and T. For the test of the formula (1) I have

chosen the observations at Indio during the nights of July 23 and 24, and at Lone Pine on August 5 and August 11. I have preferred these nights to the others because of the constancy of the humidity and the relatively great temperature difference between evening and morning values. By means of the formula connecting radiation and humidity obtained from the Algerian values at constant temperature, a small correction may be applied to these Californian observations, in order to reduce them to constant humidity. The logarithms of the radiation values thus obtained are calculated and also the logarithms of the corresponding temperatures, tables III and IV. If log E_{at} is plotted along the y-axis, log T along the x-axis, it ought to be possible to join the points thus obtained by a straight line, if the formula (2) is satisfied. The slope of this straight line ($\frac{dy}{dx}=$constant$=a$) ought in such a case to give us the value of a.

I have applied this procedure to the observations mentioned and found that within the investigated interval the logarithms of radiation and of temperature are connected to one another by a linear relation. Figure 4 gives the logarithm lines corresponding to the Indio observations. The deviations from the straight lines are somewhat larger for the Lone Pine values, but the discrepancies seem not to be systematic in their direction and I therefore think that one may regard the formula (1) as satisfied within the limits of the variation that can be expected as a result of the many atmospheric disturbances. The following table gives the values of a obtained from the observations on the four nights selected:

Place	Date	a	Weight
Indio	July 23	3.60	4
Indio	July 24	4.27	4
Lone Pine	August 5	4.4	1
Lone Pine	August 11	4.4	1

Weighted mean: $a = 4.03$.

The table shows that the value of a is subject to considerable variations, which is a natural consequence of the great variations from the average conditions, to which the atmosphere is subject. In the following pages, when I have used the value 4.0 as an average value for a, in order to reduce the various observations to a constant temperature (20° C.), this procedure is held to be justified by the preceding discussion, as well as by the fact that, in applying this method of reduction, we obtain an almost constant value for the radiation during the night, if we reduce it to a constant humidity. For all other values of a, we shall get a systematic increase or de-

TABLE III—*Radiation and Temperature*

Indio, July 23, 1913

$273+t=T$	Log T	E_{at}	Log E_{at}
302.5	2.4807	0.447	0.6503—1
301.1	2.4787	0.435	0.6385—1
298.2	2.4745	0.421	0.6243—1
297.7	2.4738	0.419	0.6222—1
296.6	2.4722	0.423	0.6263—1
296.3	2.4717	0.415	0.6180—1
295.2	2.4701	0.409	0.6117—1
294.0	2.4683	0.402	0.6042—1

Indio, July 24, 1913

$273+t=T$	Log T	E_{at}	Log E_{at}
302.5	2.4807	0.461	0.6637—1
300.5	2.4778	0.446	0.6493—1
298.0	2.4742	0.435	0.6385—1
296.9	2.4726	0.424	0.6274—1
296.0	2.4713	0.418	0.6212—1
296.0	2.4713	0.418	0.6212—1
294.2	2.4686	0.405	0.6075—1
294.2	2.4686	0.405	0.6075—1
293.6	2.4678	0.405	0.6075—1
292.5	2.4661	0.407	0.6096—1

TABLE IV—*Radiation and Temperature*

Lone Pine, Aug. 5, 1913

$273+t=T$	Log T	E_{at}	Log E_{at}
297.6	2.4736	0.391	0.5922—1
296.0	2.4713	0.374	0.5729—1
290.1	2.4624	0.336	0.5263—1
294.4	2.4689	0.374	0.5729—1
288.6	2.4603	0.336	0.5263—1
285.4	2.4555	0.333	0.5224—1
287.8	2.4591	0.335	0.5250—1
287.4	2.4585	0.343	0.5353—1
287.4	2.4585	0.351	0.5453—1

Lone Pine, Aug. 11, 1913

$273+t=T$	Log T	E_{at}	Log E_{at}
293.5	2.4676	0.376	0.5752—1
297.6	2.4736	0.393	0.5944—1
296.2	2.4716	0.388	0.5888—1
293.7	2.4679	0.367	0.5647—1
291.9	2.4652	0.343	0.5353—1
287.3	2.4583	0.337	0.5276—1
285.0	2.4548	0.324	0.5105—1
284.8	2.4545	0.323	0.5092—1
282.8	2.4515	0.313	0.4955—1
283.0	2.4518	0.334	0.5237—1
281.9	2.4501	0.319	0.5038—1

crease in the radiation with the time owing to the fact that the temperature is always falling from evening to morning.

It is of interest to find that the value of a, thus determined, is in close agreement with the value deduced by Bigelow[1] from thermodynamic considerations of the heat processes to which the atmos-

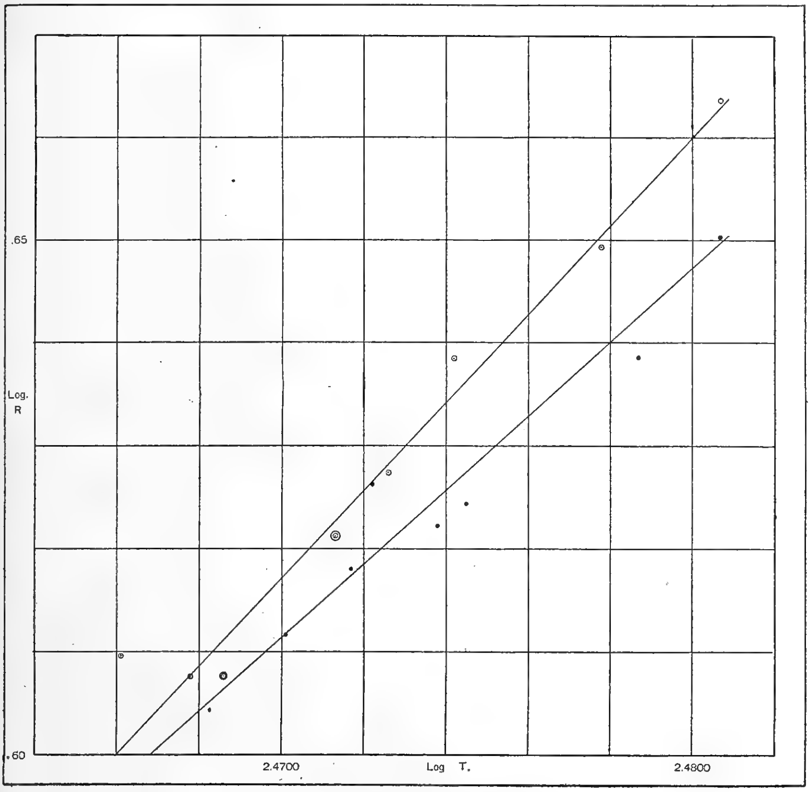

FIG. 4.—Atmospheric radiation and temperature. Indio, Cal., 1913.
$\text{Log } E_{at} = \text{Const.} + a \log T.$

phere is subject. Bigelow finds a to be equal to 3.82 and almost constant at various altitudes.

In regard to the connection that probably exists between the effective temperature of the air and the temperature at the earth's surface, I may refer to the theoretical treatment given in chapter III.

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[1] Boletín de la Oficina Meteorológica Argentina, Octubre, 1912, p. 15.

B. OBSERVATIONS ON THE SUMMITS OF MOUNT WHITNEY (4,420 M.), OF MOUNT SAN ANTONIO (3,000 M.), OF MOUNT SAN GORGONIO (3,500 M.), AND AT LONE PINE CANYON (2,500 M.).

These observations will be discussed further on in connection with the observations made simultaneously at lower altitudes. Here they will be considered separately in regard to the conditions of temperature and humidity prevailing at the high level stations. The problem to be investigated is this: Is the effective radiation, or the radiation of the atmosphere, at the high stations in any way different from the radiation found at lower altitudes, under the same conditions of temperature and humidity? Or is the average radiation of the atmosphere, at the altitudes here considered, a constant function of the temperature and the humidity? Will there not be other variables introduced when we move from one place to another at different altitudes? In the theoretical part I have pointed out some facts that ought to be considered in this connection and I then arrived at the conclusion that the effect on the radiation of temperature and humidity ought to prevail over other influences in the lower layers of the atmosphere.

The observations are given in tables 16 to 19. The tables also give the radiation of the atmosphere corresponding to each individual observation, as well as this radiation reduced to a temperature of 20° C. by means of the relation:

$$\frac{E_{\mathbf{a}t}}{E_{\mathbf{a}t_1}} = \left(\frac{T}{T_1}\right)^a$$

where a is assumed to have the same value as that obtained from our observations at Indio and at Lone Pine. The observations given in tables 16 to 19 are now arranged in tables V and VI in a way exactly similar to that which I have employed for the Algerian observations, except that in tables V and VI, I deal with the radiation of the atmosphere toward the instrument, instead of the reverse, as in table II. The relation of the two functions has been explained above.

From the tables it is seen that the Mount Whitney values, reduced in the way described, seem to fall to values a little lower than what would correspond to the form of the Algerian curve, as given above by the formula $E_{\mathbf{a}} = 0.453 - 0.134 \cdot e^{-0.10p}$. The reason for this discrepancy may be partly that the exponent a is not quite the same for thin as for thick radiating layers. This explanation is rendered unlikely by the calculations of Bigelow and the observations of Very and Paschen on radiating layers of moist air. But there are other

TABLE V—*Mt. Whitney and Mt. San Gorgonio*

ρ	0.5–1.0		1.5–2.0		2.0–2.5	
	ρ	E_a	ρ	E_a	ρ	E_a
	0.69	0.300	1.80	0.288	2.37	0.289
	0.69	0.303	1.91	0.295	2.37	0.316
	0.54	0.298	1.54	0.289	2.46	0.338
	0.54	0.297	1.88	0.274	2.46	0.337
			1.68	0.260	2.06	0.317
Means..........	0.62	0.299	1.70	0.339	2.06	0.334
			1.76	0.317	2.21	0.295
	1.0–1.5		1.76	0.306	2.21	0.267
			1.73	0.314	2.00	0.281
	ρ	R	1.81	0.312	2.00	0.262
			1.81	0.302	2.32	0.326
	1.17	0.300	1.86	0.318	2.32	0.319
	1.17	0.303	1.86	0.309	2.44	0.324
	1.02	0.325	1.90	0.304	2.44	0.327
	1.02	0.322	1.90	0.303	2.42	0.315
	1.12	0.316	1.83	0.308	2.42	0.315
	1.47	0.311	1.83	0.303	2.46	0.308
	1.47	0.393	1.93	0.298	2.46	0.314
	1.47	0.260	1.93	0.285	2.39	0.315
	1.32	0.323	1.52	0.335	2.39	0.309
	1.32	0.316	1.52	0.332	2.21	0.299
	1.40	0.316	....	.....	....	.....
	1.40	0.321	....	.....	....	.....
	1.14	0.276	....	.....	....	.....
Means..........	1.27	0.306	1.78	0.305	2.31	0.310

ρ	2.5–3.0		3.0–3.5		3.5–4.0	
	ρ	E_a	ρ	E_a	ρ	E_a
	2.95	0.300	3.07	0.351	3.80	0.277
	2.66	0.282	3.35	0.337	3.80	0.338
	2.61	0.288	3.35	0.345	3.75	0.306
	2.97	0.335	3.28	0.310	3.61	0.343
	2.90	0.344	3.28	0.304	3.79	0.345
	2.59	0.311	3.18	0.329	3.81	0.320
	2.59	0.308	3.15	0.350	3.70	0.302
	2.74	0.313	3.30	0.271	3.59	0.344
	2.74	0.302	3.23	0.327	3.59	0.330
	2.87	0.326	....	.....	3.51	0.356
	2.87	0.317	....	.....	3.51	0.351
	2.67	0.332	....	.....	....	.....
	2.67	0.317	....	.....	....	.....
Means..........	2.75	0.313	3.24	0.325	3.68	0.328

influences that are likely to produce a deviation of the same kind. Among these we will consider:

(1) The influence of the temperature gradient. It is evident that for a radiating atmosphere of low density, a larger part of the radiation reaching the surface of the earth must come from farther and therefore colder layers than for a dense atmosphere. From this it follows that a decrease in the density of the atmosphere must produce a decrease in its radiation in a twofold way: (A) in consequence of the diminished radiating power of the unit volume; and, (B) because of the simultaneous shifting of the effective radiating layer to higher altitudes.

(2) We must consider that the radiation is determined by the integral humidity, and that the water-vapor pressure comes into play only in so far as it gives a measure of this quantity. At a certain place we may obtain the integral humidity by multiplying the pressure by a certain constant; but this constant varies with the altitude. At sea level this constant has a value equal to 2.3 against 1.8 at the altitude of the summit of Mount Whitney; these values can be obtained from the formula of Süring, which has been discussed in a previous chapter.

This means that, in order to compare the integral humidities of two different localities as indicated by their absolute humidities, we should apply a reduction factor to the latter values. Thus, if the absolute humidity on the top of Mount Whitney is the same as at sea level (which naturally is unlikely to be the case at the same time), the integral humidity at the former place will be only $\frac{1.8}{2.4}$ of that at the latter.

(3) The coefficient of absorption, and consequently also that of the emission for a unit mass of water vapor, is a function of the total pressure to which it is subjected. This important fact has been revealed by the investigations of Eva von Bahr [1] who found that water vapor at a pressure of 450 mm. absorbs only about 77 per cent of what an identical quantity absorbs at 755 mm. pressure. The absorption coefficient will change in about the same proportion, and consequently the effective amount of water vapor (if we may use that term for the amount of water vapor that gives a constant radiation) will not be proportional to its mass but will be a function of the pressure, *i. e.*, a function also of the altitude. Miss v. Bahr's

[1] Eva v. Bahr, Über die Einwirkung des Druckes auf die Absorption Ultraroter Strahlung durch Gase. Inaug. Diss., Upsala, 1908, p. 65.

measurements unfortunately do not proceed farther than to the water-vapor band at 2.7 μ and include therefore a part of the spectrum that is comparatively unimportant for the "cold radiation" with which we are dealing here. The maximum of radiation from a black body at 285 degrees absolute temperature occurs at about 10 μ, and

TABLE VI—*Mt. San Antonio and Lone Pine Canyon*

ρ	1.50–2.50		2.50–3.50		3.50–4.50	
	ρ	E_a	ρ	E_a	ρ	E_a
	2.27	0.310	2.54	0.363	3.63	0.348
	2.16	0.310	2.65	0.334	3.63	0.355
	1.63	0.309	3.24	0.340	3.91	0.357
	2.27	0.313	2.60	0.346	3.91	0.350
	1.99	0.324	3.23	0.357	3.53	0.361
	2.36	0.312	....	.....	4.23	0.334
	2.22	0.321	....	.....	4.07	0.345
	2.46	0.335	....	.....	3.75	0.334
	....	.....	....	.....	4.00	0.333
Means..........	2.17	0.317	2.85	0.348	3.85	0.346

ρ	4.50–5.50		5.50–6.50		6.50–7.50	
	ρ	E_a	ρ	E_a	ρ	E_a
	4.71	0.359	6.48	0.358	7.34	0.359
	5.27	0.346	6.35	0.362	6.53	0.367
	5.32	0.351	6.35	0.352		
	5.18	0.382	6.06	0.371	6.94	0.363
	5.04	0.375	5.93	0.378		
	5.04	0.397	5.88	0.374	7.50–8.50	
	....	.....	5.52	0.375		
	....	.....	6.09	0.391	ρ	E_a
	....	.....	5.98	0.383		
	....	.....	5.98	0.386	7.85	0.356
	....	.....	6.30	0.372	7.85	0.366
	....	.....	....	.....	7.63	0.376
Means..........	5.09	0.368	6.08	0.373	7.78	0.366

therefore we cannot apply the numerical results of Miss v. Bahr to the radiation of the atmosphere.

At any rate, the conclusion seems to be justified that if we take the absolute humidity at the place of observation as a measure for the radiating power of the integral water vapor, the result would be

liable to give too high values at the higher altitude as compared with the lower one. This is actually the result of the observations. It therefore appears to me that the observations lend support to the view that the variations produced in the radiation of the lower atmosphere by a change of locality or by other influences are due to changes in the radiating power of the water vapor; changes that we are able to define, within certain limits, from observations of the temperature and the humidity at the surface of the earth.

I have now, without venturing to emphasize the absolute reliability of the procedure, applied a correction to the observed vapor pressure at different altitudes, in order that the pressure may give a true measure of the integral radiating power of the water vapor. Considering that at the altitude of Mount Whitney, the constant K in Süring's formula is 1.8, and that the total pressure there is only 44 cm., so that the absorption coefficient according to Miss v. Bahr's observations should be $\frac{16.5}{21.5}$ of the value corresponding to $p=66$ cm. (Lone Pine, Bassour), and finally that the pressure ought to be reduced to the temperature 20° C., I have used the reduction factor

$$\frac{1.8}{2.2} \cdot \frac{16.5}{21.5} \cdot \frac{273}{293} = 0.68$$

for the humidity values taken at the summit of Mount Whitney (4,420 m.) and also for Mount San Gorgonio (3,500 m).

A similar consideration gives the reduction factor

$$\frac{2.0}{2.2} \cdot \frac{19.5}{21.5} \cdot \frac{288}{273} = 0.84$$

for the measurements at Mount San Antonio (3,000 m.) and at Lone Pine Canyon (2,500 m.).

In this way the values plotted in figure 5 are obtained. We are now able to draw a continuous curve through the points given by the observations corresponding to various altitudes. With regard to the considerations that I have brought forward in the theoretical part, I have tried an expression of the form

$$E_a = K - Ce^{-\gamma p}$$

where

$$K = 0.439,\ C = 0.158,\ \text{and}\ \gamma = 0.069.$$

This gives a fairly good idea of the relation between the radiation of the atmosphere at 20° C. and the humidity. The curve corresponding to this equation is given by a dotted line in figure 5. The expression adopted here does not fit the observations at high pressures so

well as the expression given in connection with the discussion of the values obtained at Bassour, but it is better adapted to include in a general relation all the observations at different altitudes. As may be seen from the figure, the deviation from the curve is often considerable for single groups of values, but this can easily be explained as being due to deviations of the state of the atmosphere from its

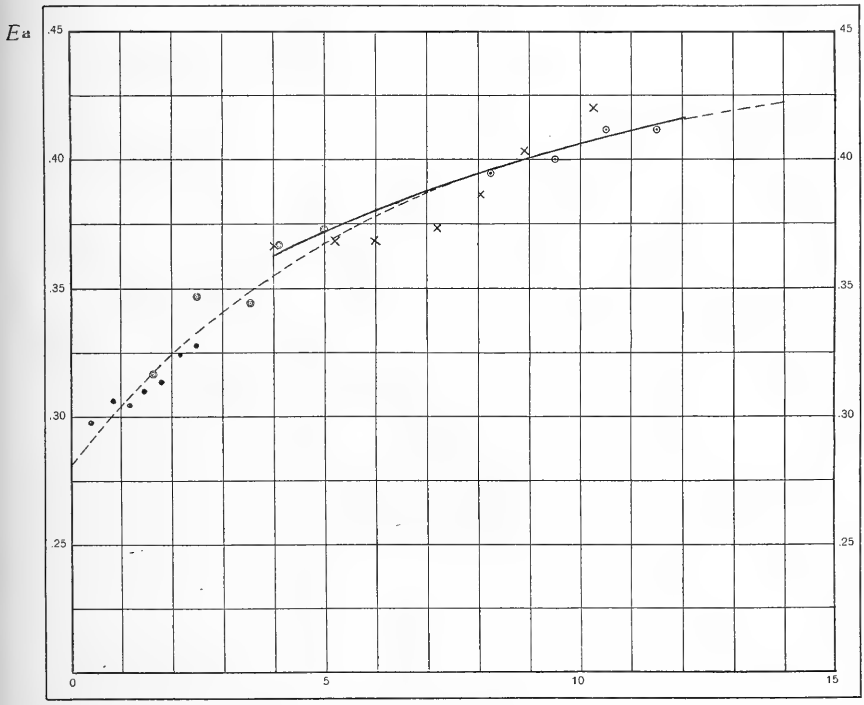

FIG. 5.—Humidity and Radiation of the Atmosphere.

Circles represent observations at Indio. Double circles represent observations at Mount San Antonio and at Lone Pine Canyon. Crosses represent observations at Lone Pine. Points represent observations at Mount San Gorgonio and at Mount Whitney.

normal conditions and also to the fact that the mean value is often calculated from a few observations.

It seems to me that the form of this curve enables us to draw some interesting conclusions about the radiation from the different constituents of the atmosphere. It must be admitted that the shape of the curve in the investigated interval does not allow of drawing any safe conclusions for points outside this interval, and particularly, as will be shown further on, the curve does not approach a limiting

value of 0.439 cal. for very large values of ρ, as one would expect from the expression that has been adopted. On the other hand, the observations bring us very near the zero value of humidity and the question arises, whether we may not be entitled to attempt an extrapolation down to zero without causing too large an error in the limiting value. We wish to answer the question: how does the atmosphere radiate, if there is no water vapor in it? As I have pointed out previously, the possibility of an extrapolation to zero is doubtful, because in the non-homogeneous radiation of the water vapor there are certainly terms corresponding to wave lengths, where even very thin layers radiate almost to their full value. Consequently these have scarcely any influence upon the variations of the radiation from thicker layers. Will the curve that gives the relation between the radiation and the radiating mass of water vapor for values of the humidity lower than 0.4 show a rapid decline of which no indication is apparent in the investigated interval 0.4 – 12 mm.? For comparison I may refer to a curve drawn from a calculation by N. Ekholm[1] of the transmission of water vapor according to Langley and Rubens and Aschkinass. The curve represents the radiation from a black body at 15° temperature as transmitted through layers of water vapor of variable thickness. The same curve evidently also gives the radiation from the identical vapor layers, provided that the law of Kirchhoff holds, and that the water vapor itself is at 15°.

As far as the result may be depended upon, it apparently shows that laboratory measurements give no evidence whatever of a sudden drop in the radiation curve for very thin radiating layers. It would be rather interesting to investigate the radiation of the atmosphere compared with the radiation of the water vapor and of the carbon dioxide and possibly also that of the ozone contained in the upper layers, with proper regard to the temperature conditions and to careful laboratory measurements on the absorption and radiation of these gases. A first attempt in this direction is made by Ekholm. However, it appears to me that he does not give due attention to the fact that the magnitude of the effective radiation to space depends upon the capacity of the atmosphere to radiate back to the earth, and only indirectly upon the absorption capacity of the atmosphere. Quantitative calculations of the radiation processes within the atmosphere must necessarily take into consideration the temperature conditions in various atmospheric layers. The laboratory measurements upon which such a computation should be based are as yet very in-

[1] Met. Zt., 1902, pp. 489-505.

complete and rather qualitative than quantitative, at least as regards water vapor. I have reason to believe that the careful observations of Fowle, of the Astrophysical Observatory of the Smithsonian Institution, will in the near future fill this gap.

From analogy with the absorbing qualities of water vapor, I think one may conclude that an extrapolation of the radiation curve (fig. 5) down to zero is liable to give an approximately correct result. The extrapolation for the radiation of a perfectly dry atmosphere at 20° C. gives a value of 0.281, which corresponds to a nocturnal radiation of 0.283 at the same temperature. At 0° C. the same quantities are 0.212 and 0.213 cal. and at −8° they have the values 0.190 and 0.191, respectively. The latter value comes near the figure 0.201, obtained by Pernter on the top of Sonnblick at −8° C. temperature.

These considerations have given a value of the radiation from a perfectly dry atmosphere, and at the same time they lead to an approximate estimate of the radiation of the upper atmosphere, which is probably chiefly due to carbon dioxide and a variable amount of ozone. The observations indicate a relatively high value for the radiation of the upper layers—almost 50 per cent of the radiation of a black body at the prevailing temperature of the place of observation. Hence the importance of the upper atmosphere for the heat-economy of the earth is obvious. The effect at places near the earth's surface is of an indirect character, as only a small fraction of the radiation from the upper strata reaches the earth's surface. But the importance of the upper layers for the protecting of the lower water-vapor atmosphere—the troposphere—against loss of heat, is entirely similar to the importance of the latter for the surface conditions of the earth. If we could suddenly make the upper atmosphere disappear, the effect would scarcely be appreciable at the earth's surface for the first moment. But the change would very soon make itself felt through a considerable increase in the temperature gradient. At places situated a few kilometers above the earth's surface, as, for instance, the summits of high mountains, the temperature would fall to very low values. As a consequence the conduction and convection of heat from the earth's surface would be considerably increased. Keeping these conditions in view, and in consideration of the high value of the radiation of the upper atmosphere—the stratosphere—indicated by the observations, I think it very probable that relatively small changes in the amount of carbon dioxide or ozone in the atmosphere, may have considerable effect on the temperature conditions of the earth. This hypothesis was first advanced by Arrhenius, that

the glacial period may have been produced by a temporary decrease in the amount of carbon dioxide in the air. Even if this hypothesis was at first founded upon assumptions for the absorption of carbon dioxide which are not strictly correct, it is still an open question whether an examination of the "protecting" influence of the higher atmospheric layers upon lower ones may not show that a decrease of the carbon dioxide will have important consequences, owing to the resulting decrease in the radiation of the upper layers and the increased temperature gradient at the earth's surface. The problem is identical with that of finding the position of the effective layer in regard to the earth's radiation out to space. I propose to investigate this subject in a later paper, with the support of the laboratory measurements which will then be available.

C. OBSERVATIONS AT INDIO AND LONE PINE

Knowing the influence of temperature upon the radiation of the atmosphere, I can reduce the radiation values obtained at different places to a certain temperature. The function giving the relation between radiation and water-vapor content ought to be the same for every locality. Reducing the observations at Bassour, at Lone Pine, and at Indio (see tables VII and VIII) to 20° C., and plotting the mean values, we obtain a diagram of the aspect shown in figure 5. The values from Algeria are given by the smooth curve. The observations from Lone Pine (crosses) and the observations from Indio (circles) deviate more or less from the Algerian curve. Considering, however, that they are founded upon a very limited number of nights (Lone Pine 8, Indio 3), and that the mean deviation for all points is very inconsiderable, the result must be regarded as very satisfactory.

In regard to the general meteorological conditions at Lone Pine, it must be said that this place proved to be far from ideal for this kind of observation, the principal purpose here being, not to collect meteorological data, but to test a general law. The rapid changes in temperature and humidity during the nights must have had as a result that the atmosphere was often under very unstable conditions, widely differing from what may be regarded as the average. This is obvious also from the balloon observations of the U. S. Weather Bureau, made simultaneously with my observations during a couple of evenings at Lone Pine. These observations, made up to about 2,000 meters above the place of ascent, showed that there were often considerable deviations from the conditions defined by "the con-

TABLE VII—*Lone Pine*

ρ	3.50–4.50		4.50–5.50		5.50–6.50		6.50–7.50		7.50–8.50		8.50–9.50	
	ρ	E_a	ρ	E_a	ρ	E_a	ρ	E_a	ρ	E_a	ρ	E_a
	3.67	0.374	5.46	0.363	5.87	0.366	6.90	0.356	8.23	0.389	8.54	0.415
	3.67	0.382	4.71	0.381	5.79	0.358	6.99	0.397	8.05	0.387	8.99	0.419
	3.85	0.377	4.71	0.362	6.33	0.359	7.08	0.395	7.61	0.371	9.01	0.374
	3.85	0.346	5.30	0.369	5.97	0.360	7.07	0.385	8.39	0.411		
	4.49	0.368	5.30	0.371	5.96	0.379	7.47	0.399	8.11	0.407		
	4.49	0.357	5.08	0.363	6.40	0.377	7.48	0.359	8.13	0.406	8.85	0.403
	....	.....	5.08	0.352	6.12	0.381	7.48	0.369	8.03	0.408		
	....	.....	5.26	0.380	6.12	0.356	7.31	0.372	7.61	0.394		
	....	.....	5.26	0.389	5.78	0.371	7.31	0.369	8.29	0.394	9.50–11.50	
	....	.....	4.69	0.338	5.78	0.371	6.59	0.358	7.99	0.387		
	....	.....	5.37	0.365	5.78	0.363	6.59	0.522	7.38	0.360	ρ	E_a
	....	.....	5.16	0.364	5.78	0.358	6.96	0.378	7.59	0.378		
	....	.....	5.16	0.385	6.18	0.359	6.52	0.375	8.39	0.376		
	....	.....	5.36	0.349	6.18	0.372	7.18	0.394	8.43	0.395	10.01	0.407
	....	.....	5.36	0.356	5.78	0.351	7.18	0.374	8.29	0.402	10.24	0.419
	....	.....	5.42	0.405	5.78	0.365	7.25	0.360	8.47	0.379	10.50	0.423
	....	.....	....	.....	6.27	0.343	7.25	0.368	7.73	0.386	10.58	0.426
	....	.....	....	.....	6.27	0.384	7.38	0.373	8.28	0.389	10.20	0.420
	....	.....	....	.....	5.91	0.382	7.38	0.370	8.00	0.384	9.71	0.433
	....	.....	....	.....	5.91	0.397	7.48	0.359	8.44	0.389	10.11	0.415
	....	.....	....	.....	5.56	0.369	7.48	0.369	8.01	0.393	.....	.....
	....	.....	....	.....	5.56	0.367	....	.....	8.01	0.400	.....	.....
	....	.....	....	.....	....	.....	....	.....	8.23	0.393	.....	.....
	....	.....	....	.....	....	.....	....	.....	7.52	0.337	.....	.....
	....	.....	....	.....	....	.....	....	.....	7.52	0.347	.....	.....
	....	.....	....	.....	....	.....	....	.....	7.61	0.365	.....	.....
Means . .	4.00	0.367	5.17	0.368	5.96	0.368	7.16	0.373	8.02	0.386	10.19	0.420

stant temperature gradient" and by Süring's formula for the water-vapor pressure.

But the purpose of observations of the kind here described is a double one. In the first place, to find the general law for the average conditions, and in the second place to give an idea of the deviations likely to occur from these average conditions.

TABLE VIII—*Indio*

ρ	8.0–9.0		9.0–10.0			
	ρ	E_a	ρ	E_a		
	8.15	0.400	9.65	0.397	.....	.....
	8.43	0.393	9.37	0.398	.....	.....
	8.81	0.393	9.30	0.399	.....	.....
	....	.....	9.65	0.404	.....	.....
Means	8.46	0.395	9.49	0.400	.....	.....

ρ	10.0–11.0		11.0–12.0			
	ρ	E_a	ρ	E_a		
	10.31	0.402	11.86	0.436	.....	.....
	10.69	0.405	11.43	0.433	.....	.....
	10.97	0.410	11.13	0.438	.....	.....
	10.82	0.396	11.33	0.396	.....	.....
	10.52	0.395	11.30	0.391	.....	.....
	10.52	0.397	11.56	0.394	.....	.....
	10.47	0.402	11.41	0.396	.....	.....
	10.67	0.435	.....	.....	.....	.....
	10.77	0.440	.....	.....	.....	.....
	10.64	0.436	.....	.....	.....	.....
Means.........	10.64	0.412	11.43	0.412	.....	.....

D. THE EFFECTIVE RADIATION TO THE SKY AS A FUNCTION OF TIME

Exner[1] has made a comparison between the radiation values obtained at different hours of the night on the top of Sonnblick. He finds that there are indications of a maximum of radiation in the morning before sunrise.

[1] Met. Zeitschrift (1903), 9, p. 409.

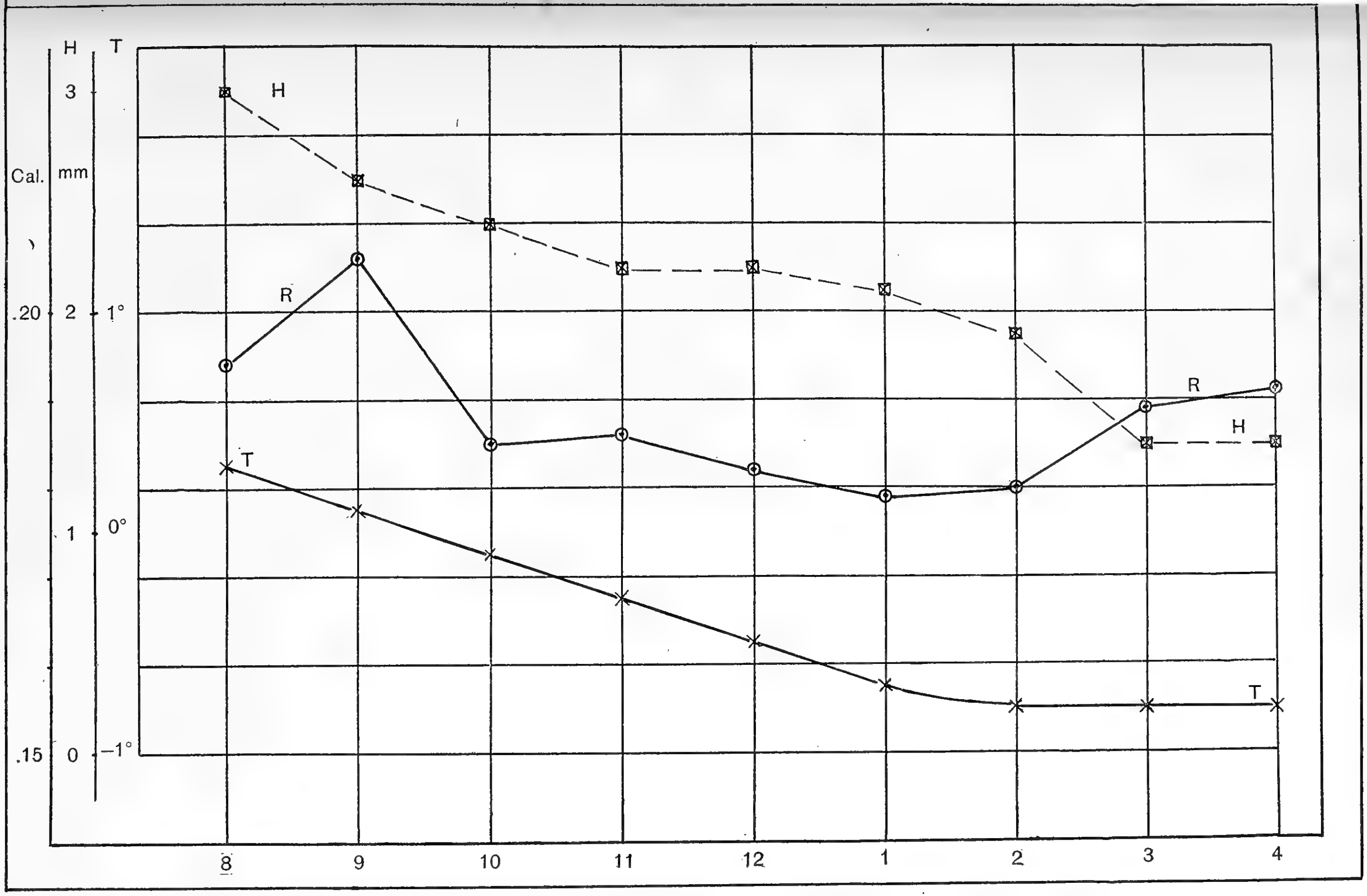

FIG. 6.—Mt. Whitney Night Observation of Humidity (H), Radiation (R), and Temperature (T).

From the observations on the nights of August 3, 4, 5, and 11 on the summit of Mount Whitney (during these nights the observations were carried on continuously from evening to morning), I have computed the means of the radiation, the temperature, and the humidity, corresponding to different hours. The result is given by figure 6, where the curve *RR* corresponds to the radiation; the curves *HH* and *TT* to the humidity and the temperature, respectively. The radiation decreases slowly from 9 o'clock in the evening to about 2 o'clock in the morning. At about 2:30 the radiation is subjected to a rapid increase; between 3 and 4 o'clock it keeps a somewhat higher value than during the rest of the night. The temperature, which shows a very continuous decrease from evening to morning, evidently cannot be regarded as a cause for these conditions. An examination of the humidity conditions shows however that the absolute humidity is subjected to a very marked decrease, which is perfectly simultaneous with the named increase in the effective radiation. Considering that the previous investigations, discussed in this paper, show that low humidity and high radiation correspond to one another, we must conclude that the maximum of radiation occurring in the morning before sunrise, is caused by a rapid decrease of the humidity at that time. It seems very probable to me that the maximum obtained by Exner from his observations on Sonnblick, may be explained in the same way.

E. INFLUENCE OF CLOUDS

The influence of clouds upon the radiation processes within the atmosphere is of very great importance for many meteorological questions. At the same time the problem is an immensely difficult one, because of the irregularities of the fundamental phenomenon itself. Take the question of the influence of the conditions of the atmosphere upon the amount of radiation reaching us from the sun. When the sky is clear, we can probably calculate from a single observation, or a couple of observations, together with one or two known facts, the whole access of radiation during the day to within perhaps 5 per cent. But as soon as clouds are present, we have to fall back upon continuous observations, the occurrence and density of the clouds, and the time of their appearance being subject to no known general law that holds for such small intervals of time as we wish to consider. Moreover the influence of clouds upon the solar radiation is very great, the radiation being reduced to a very small fraction of its former value by the interference of a cloud. Similar conditions hold in regard to the effective radiation to the sky. As this

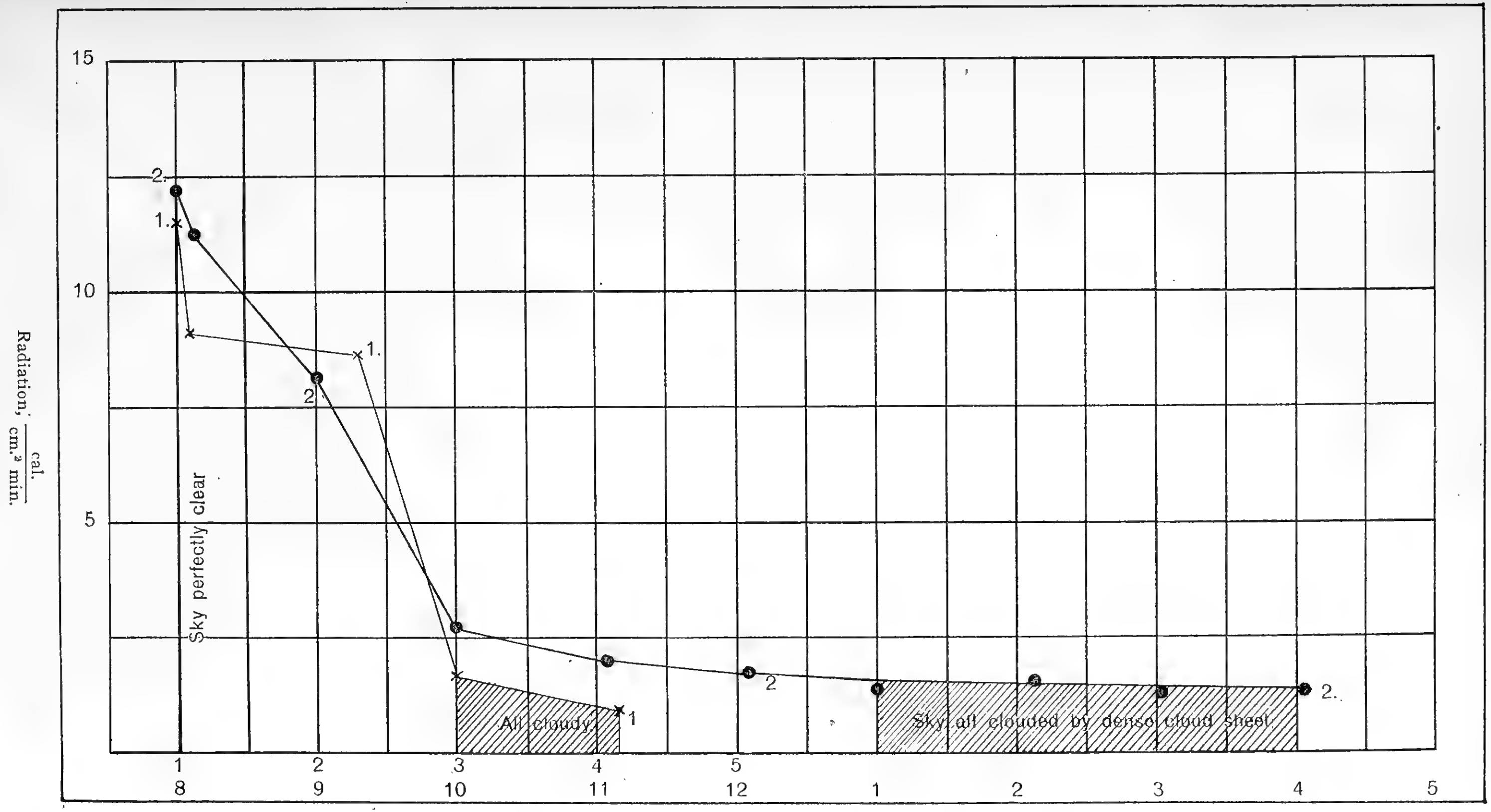

FIG. 7.—Effect of clouds on nocturnal radiatior Curve 1: Claremont, Cal., July 12, 1^h to 5^h. Curve 2: Claremont, Cal., July 13, 8^h to 4^h

radiation goes out in all directions, the influence of a single cloud will be more continuous than is the case for the solar radiation. As soon as the cloud comes over the horizon it will begin to affect the radiation to the sky, its influence growing as it approaches the zenith. This will be rendered clearer, and details will be afforded, by the observations on the radiation to different parts of the sky, given in a later chapter.

It is evident that, when the sky is cloudy, we can distinguish between three radiation sources for the atmospheric radiation: First, the radiation from the parts of the atmosphere below the clouds; secondly, the part of the radiation from the clouds themselves, which is able to pass through the inferior layer, and, in the third place, the radiation from the layers above the clouds, of which probably, for an entirely overcast sky, only a very small fraction is able to penetrate the cloud-sheet and the lower atmosphere.

Some measurements were taken in the case of an entirely overcast sky. Figure 7 shows two curves drawn from observations at Claremont. In the beginning the sky was perfectly clear, at the end it was entirely covered by a low, dense cloud-sheet: cumulus or strato-cumulus.

In general the following classification seems to be supported by the observations:

	Average radiation
Clear sky	0.14-0.20
Sky entirely overcast by:	
Cirrus, cirrostratus and stratus	0.08-0.16
Alto-cumulus and alto-stratus	0.04-0.08
Cumulus and strato-cumulus	0.01-0.04

Especially in the northern winter climate, the sky is very often overcast by more or less dense sheets of stratus clouds. They are very often not dense enough to prevent the brighter stars being very easily seen through them, and especially in the night it is therefore often difficult to tell whether the sky is perfectly clear or not. Dr. Kennard proposed to me that one should use the visibility of the stars (1st, 2d, 3d, and 4th magnitude, etc.) to define the sky, when it seemed to be overcast or very hazy. This may be of advantage, especially when observations are taken in the winter time or extended to hazy conditions.

CHAPTER VI

RADIATION TO DIFFERENT PARTS OF THE SKY[1]

In the foregoing chapters an account has been given of observations showing the influence of humidity and temperature conditions upon the effective radiation to the sky. There the total radiation to the sky was considered, independent of the fact that this radiation takes place in different directions. The thing measured represented an integral over the whole hemispherical space. About the different terms constituting the sum this integral gives us no idea.

In the historical survey I have referred to the interesting investigations of Homén, and mentioned his observations of the nocturnal radiation to *different parts of the sky*. Homén observed, with a somewhat modified Ångström pyrheliometer, of type 1905, where two metal disks were exposed to the sky alternately and their temperature difference at certain moments read off. In order to measure the radiation in various directions Homén used a screen arrangement, which screened off certain concentric zones of the sky. The chief objection to this method seems to me to be that the radiating power of the soot will be introduced as a variable with the direction, and as this quantity is not very well defined an error will probably be introduced, which, however, can scarcely amount to more than about 2 per cent. Homén found that the distribution of the radiation upon the different zones of the sky was almost constant for different values of the total radiation. As Homén's measurements have since been employed in extending, to represent the whole sky,[2] observations of the radiation toward a limited part of the sky, and as the question itself seems to be of interest for the knowledge of atmospheric radiation in its dependence upon other conditions, I have thought it valuable to investigate in what degree this distribution of radiation over the sky is subject to variations. For this purpose the arrangement shown schematically in figure 8 was found to be a satisfactory one.

To the electrical compensation instrument, which has been described, can be attached a hemispherical screen, *abcdef,* whose radius is 7.1 cm. From this screen can be removed a spherical cap *cd,* which

[1] Large parts of this chapter were published in the Astrophysical Journal, Vol. 39, No. 1, January, 1914.

[2] Exner (1903), *loc. cit.*

leaves a hole of 32° plane angle open to the sky. The screen is brightly polished on the outside, but blackened on the inside, in order to avoid multiple reflections.

The instrument to which this arrangement was attached was pointed to different parts of the sky, and the zenith angle was read in a circular scale, as is shown in figure 8. The value of the radiation within the solid angle *csd* (32°) was obtained in the usual way

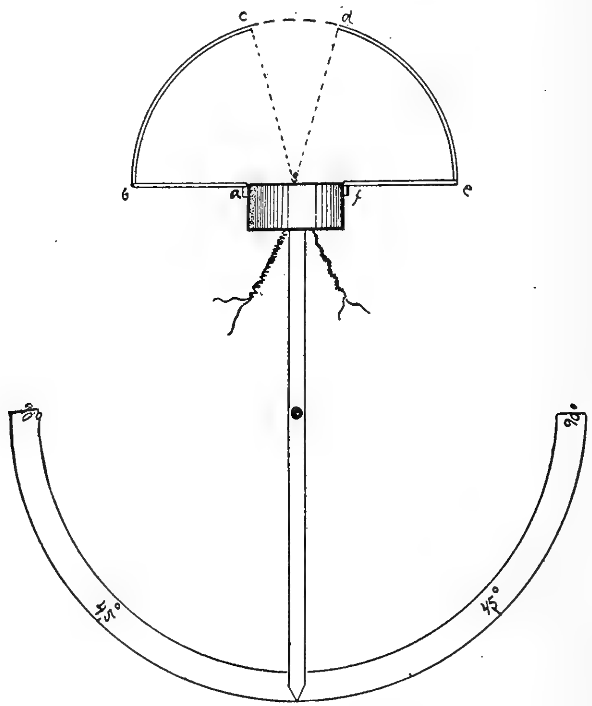

Fig. 8.—Apparatus used for determining the radiation to different parts of the sky.

by determining the compensation current through the black strip. This arrangement has two obvious advantages over a bolometer arranged in a similar way. In the first place, the instrument is very steady and quite independent of air current, because both strips are here exposed in exactly the same way. The readings must further be quite independent of the position of the strips, it being possible to turn the instrument over in different directions without change in the sensitiveness. Everyone who is familiar with bolometric work knows the difficulty that sometimes arises from the fact that the

sensitiveness of the bolometer changes with its position, the conductivity of heat from the strips through the air being different for vertical and horizontal positions. On the other hand, the sensitiveness of my apparatus, used in this way, was not very great. When the instrument was directed to points near the horizon the deflection of the galvanometer seldom amounted to more than about 2 mm., and for zenith position the deflection was about 6 mm. The probable error in every measurement is therefore about 5 per cent. In spite of this disadvantage, a comparison between the values of the total radiation observed and the total radiation computed from the observations of the radiation to the different zones shows a fairly close agreement.

If the dimensions of the strips can be regarded as negligible in comparison with the radius of the screen, we may assume the effective solid angle to be equal to the solid angle under which the central point of the instrument radiates to the hole. Now this is not exactly the case, and in computing the total radiation from the radiation to the limited parts of the sky, we must apply a correction with regard to the position of the strips. The mean solid angle is obtained through an easily effected but somewhat lengthy integration process given in the foot-note.[1] It is found to be 768.6°.

The correction term will make 1.5 per cent in the solid angle, a quantity that is not negligible when we wish to calculate the total radiation.

When the instrument is pointed in different directions, different parts of the strips will radiate to slightly different regions of the sky. In the process used for finding the distribution of radiation

[1] Let us consider a circular hole of the radius ρ, radiating to a plane surface, parallel with the hole and at the vertical distance R from it. We wish to find the radiation T to a little elementary surface, $d\tau$, whose distance from the perpendicular from the central point of the hole, is l. Using cylindric coordinates, and defining the element of the hole (do), through the relation:

$$do = \rho_1 d\phi d\rho_1$$

we get:

$$dT = \frac{R^2 \rho_1 d\phi d\rho}{[R^2+\rho_1^2+l^2-2\rho_1 l \cos\phi]^2} \cdot d\tau$$

and for the radiation from the entire hole:

$$T = \int_0^a \int_0^{2\pi} \frac{a_1 da d\phi}{[1+a_1^2+\beta^2-2a_1\beta\cos\phi]^2} \cdot d\tau$$

where we have put:

$$a = \frac{\rho}{R}; \quad a_1 = \frac{\rho_1}{R}; \quad \beta = \frac{l}{R}$$

from the single measurements this would introduce a complication if the instrument were not always turned over so that the strips were parallel to the earth's surface. When this precaution is observed, we may regard the influence of the dimensions of the strips as negligible.

If α and β are not large, so that higher powers than the fourth may be neglected, the integration gives:

$$T = \pi\alpha^2 (1 - \alpha^2 - 2\beta^2)\, d\tau \qquad (1)$$

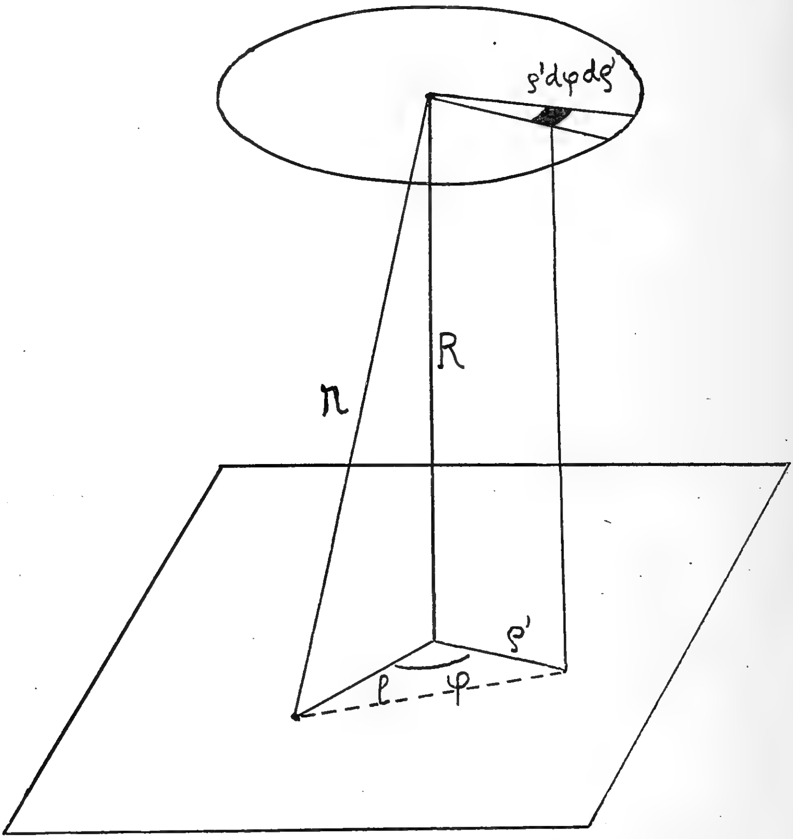

FIG. 9.

Now we proceed to consider the case, where the hole radiates to a strip of negligible width ds and of the length 2 m. The line is symmetrical in regard to the perpendicular from the central point of the hole. For the central point of the line we put: $l = n$. Then we have:

$$d\tau = dm' ds$$

$$\beta^2 = \frac{l^2}{R^2} = \frac{m'^2 + n^2}{R^2}$$

The results of these measurements for various conditions are given in table IX. Four series, representing different conditions

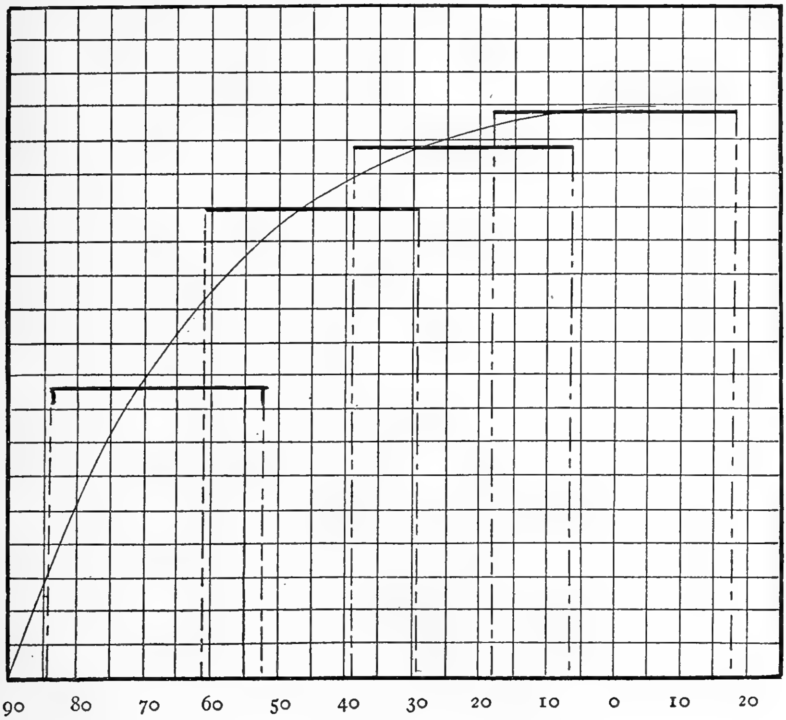

FIG. 10.

in regard to the prevailing humidity, were taken at Bassour, Algeria, at a height of 1,160 m. above sea level. Two series were taken on

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Introducing this in (1) and integrating between the limits o and m, we obtain for the radiation to the whole strip:

$$T' = \pi m a^2 \left[1 - a^2 - \frac{2\left(m^2 + \frac{n^2}{3}\right)}{R^2} \right] ds \qquad (2)$$

My instrument contained two radiating strips: For the one was: $m = 9.0$; $n = 2.0$. For the other one: $m = 9.0$ and $n = 6.0$. Further I had: $R = 68.3$; $\rho = 19.6$.

As my unit of radiation, I will now define the radiation from a surface equal to the surface of the strips within a solid angle whose cross-section is a square, and each side of which subtends one degree. Introducing the given values of a, m, n and R in (2), I then find that the mean radiation from the two strips is 768.6 times my unit of radiation.

top of Mount Whitney, 4,420 m. above sea level. In every instance the sky was perfectly clear and appeared perfectly uniform. It will be shown later on, that there is also strong experimental evidence for the perfect uniformity of the sky.

In order to obtain from the observations a more detailed idea of the effective radiation to different parts of the sky, I proceeded in the following way: In a system of coordinates, where the zenith angle is plotted along the x-axis, the magnitude of the radiation along the y-axis, every measurement with the instrument corresponds to an integral extending over 32° and limited by the x-axis and a certain curve—the distribution curve of radiation. If the measurements are plotted as rectangular surfaces, whose widths are 32° and whose heights are proportional to the magnitude of the radiation, we obtain from the observations a system of rectangles like those in figure 10. A curve drawn so that the integrals between the limits corresponding to the sides of the rectangles are equal to the areas of these rectangles will evidently be a curve representing the radiation as a function of the zenith angle.

(NOTE.—Against this procedure it can be objected that the observations do not really correspond to rectangular surfaces, the opening being circular and not square. The consequence will be that the real distribution curve will cut the rectangles in points lying nearer their central line than the section points defined by the procedure described. In fact this will alter the form of the curves very slightly; in drawing them the conditions just mentioned have been taken into consideration.)

In figures 11A and 11B the curves are shown. They indicate the fact—which has already been pointed out by Homén—that the effective radiation to a constant area of the sky decreases with an increase in the zenith distance. My observations indicate very strongly that the radiation approaches the zero value, when the zenith angle approaches 90°, which shows that the lower atmosphere, taken in very thick layers, radiates like a black body. If there were no radiating atmosphere at all, the distribution curve would be a straight line parallel to the x-axis.

A comparison between the different curves shows, further, that they differ in a very marked way from one another in regard to their form. It is also evident that this difference in form is very closely connected with the density conditions of the atmosphere and especially with its content of water vapor.

TABLE IX

Date	H	t	0°	½·45°	45°	$\frac{3}{2}$·45°	Total Rad.	Computed	Diff.
1913 11:8[1]	1.47	—2°	$\left.\begin{matrix}0.0158\\0.0155\end{matrix}\right\}0.0157$	$\left.\begin{matrix}0.0158\\0.0155\end{matrix}\right\}0.0157$	$\left.\begin{matrix}0.0151\\0.0147\end{matrix}\right\}0.0149$	$\left.\begin{matrix}0.0129\\0.0124\end{matrix}\right\}0.0127$	0.194	0.197	+0.003
8:8[1]	3.6	—1°	$\left.\begin{matrix}0.0146\\0.0144\end{matrix}\right\}0.0145$	$\left.\begin{matrix}0.0147\\0.0142\end{matrix}\right\}0.0145$	$\left.\begin{matrix}0.0134\\0.0138\end{matrix}\right\}0.0136$	$\left.\begin{matrix}0.0111\\0.0110\end{matrix}\right\}0.0111$	0.168	0.176	+0.008
1912 23:8[2]	3.8	20.8°	0.0173	0.0167	0.0164	0.0120	0.192	0.197	+0.005
4:9[2]	5.0	11.1°	0.0168	0.0157	0.0140	0.0086	0.169	0.176	+0.007
30:8[2]	7.1	20.3°	0.0158	0.0147	0.0127	0.0062	0.157	0.150	—0.007
20:8[2]	13.2	18.9°	0.0153	0.0151	0.0126	0.0041	0.145	.....	.....
									+1.8%

[1] Mt. Whitney (altitude 4,420 m.). [2] Bassour, Algeria (altitude 1,160 m.).

Together with the observations treated in the foregoing chapters, the present result gives us support for the following conclusions:

1. An increase in the water-vapor pressure will cause a decrease in the effective radiation to every point of the sky.

2. The fractional decrease is much larger for large zenith angles than for small ones.

If we regard the atmosphere as a plane parallel layer, having uniform density, ρ, and a temperature uniformly equal to the temperature at the earth's surface, the effective radiation of a certain wave length, λ, in different directions, may be expressed by

$$J_\lambda = Ce^{-\gamma \cdot \frac{\rho}{\cos \phi}} \tag{1}$$

where C and γ are constants and ϕ is the zenith angle. For another density, ρ', of the radiating atmosphere we have:

$$J'_\lambda = Ce^{-\gamma \frac{\rho'}{\cos \phi}} \tag{2}$$

and from (1) and (2):

$$\frac{J_\lambda}{J'_\lambda} = e^{-\gamma \left[\frac{\rho - \rho'}{\cos \phi}\right]} \tag{3}$$

If ρ is greater than ρ', J_λ will always be less than J'_λ. It is evident from the relation (3) that the ratio between J_λ and J'_λ diminishes as the zenith angle approaches 90°. The general behavior of the radiating atmosphere is therefore consistent with the case that only a single wave length is radiated and absorbed. But the detailed conditions are naturally very complicated through the lack of homogeneity of the radiation. Especially for the curves corresponding to high humidity the radiation falls off much quicker with the approach to the horizon than is to be expected from the dependence of the total radiation on the humidity. Especially is this the case after we have reached a value of the zenith angle of about 60 or 70 degrees. In part this is due to the increasing influence of the radiation of wave lengths whose radiation coefficients are small and can be neglected for smaller air masses, but which for the very large air masses that correspond to zenith angles not far from 90° must come into play and produce a rapid decrease of the effective radiation to points near the horizon. But here other influences are also to be considered. The observations of the total radiation, compared in regard to the diffusing power of the atmosphere for visible rays, show that the influence of diffusion can be neglected in comparison with the other more fundamental influences, as far as the total radia-

tion is concerned. But in regard to the radiation to points near the horizon we must consider that the corresponding air masses become very large and that effects of dust and haze and other sources of lack of homogeneity in the air must be introduced in quite a marked way.

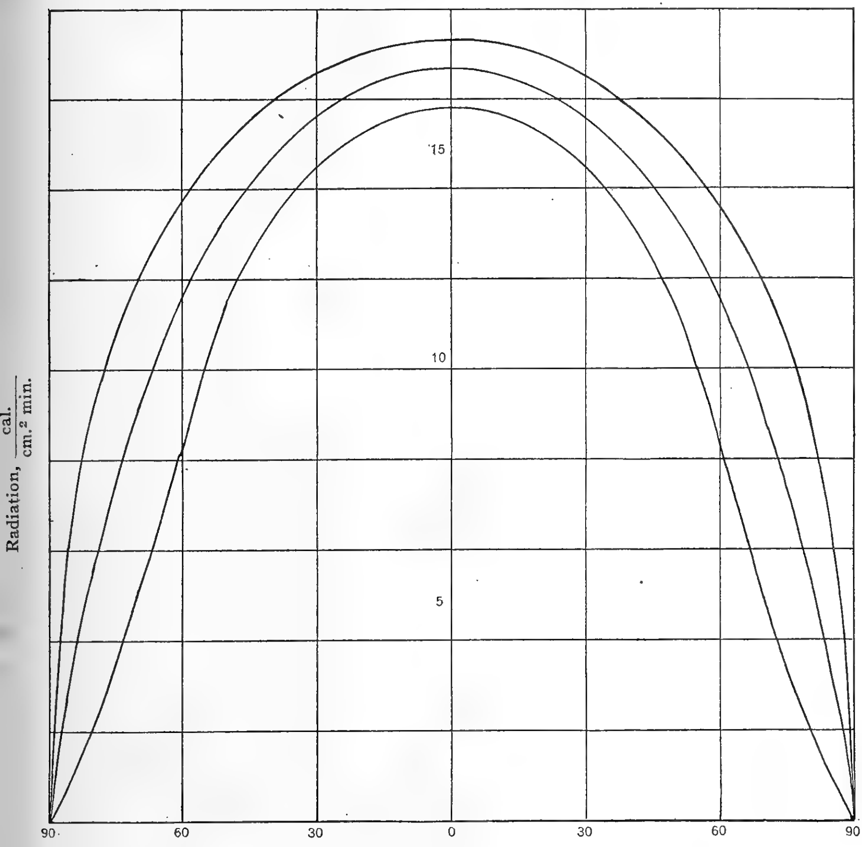

FIG. 11A.—Radiation to different parts of the sky. Bassour observations.

The curves in figures 11A and 11B represent the effective radiation within the unit of the solid angle in different directions from a surface perpendicular to the radiated beam. From these curves we can compute the radiation from a horizontal surface, like the earth's surface, to the different zones of the sky. If the radiation within a solid angle one degree square is R, the radiation (J) to the whole zone, whose width is one degree, is expressed by:

$$J = R \cos \phi \sin \phi \cdot 360 \qquad (1)$$

where ϕ is the zenith angle. For the radiation E to the whole sky, we consequently have:

$$E = 360\int_0^{\frac{\pi}{2}} J d\phi = 360\int_0^{\frac{\pi}{2}} R \cos\phi \sin\phi d\phi \qquad (2)$$

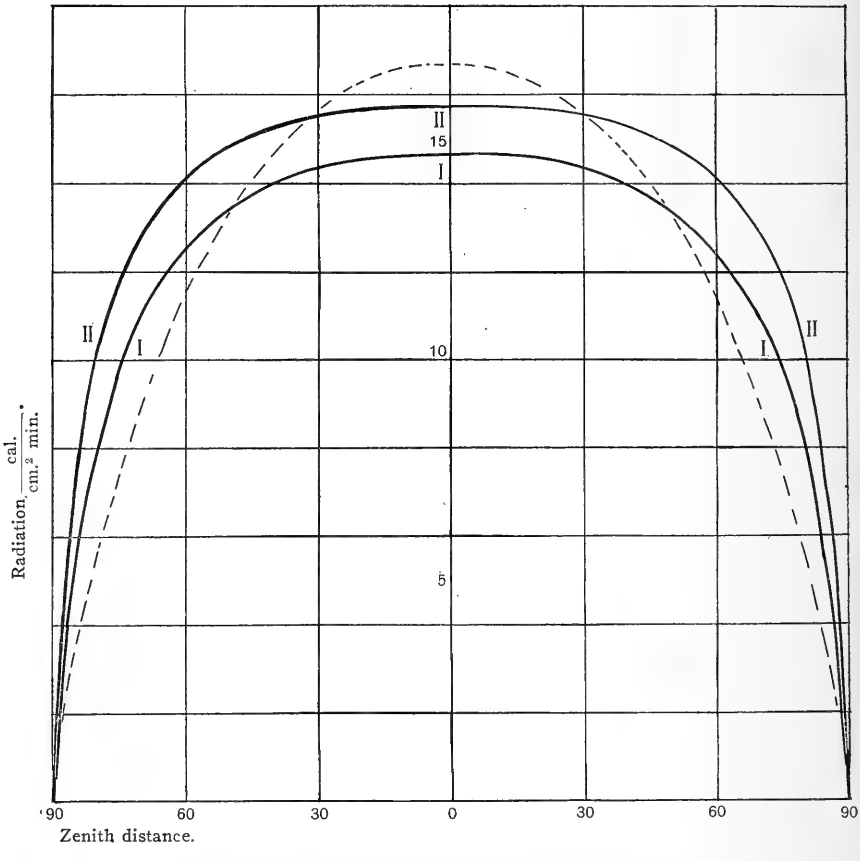

FIG. 11B.—Radiation to different parts of the sky. Curves I, II: Mt. Whitney, 1913. Water-vapor pressure; 3.6 and 1.5 mm. Hg. Curve dotted, Bassour, 1912. Water-vapor pressure; 5 mm. Hg. Temperature of instrument higher at Bassour. Compare table IX.

This integration can conveniently be effected in a mechanical way by measuring the areas given by (1). The curves that represent the radiation from a horizontal surface to different parts of the sky are shown in figure 12. The whole areas included between the curves and the x-axis must be proportional to the total radiation. In measuring the areas we must take into consideration the fact that the

ordinates represent the radiation within a solid angle of 768.6° and consequently ought to be divided by the same number. The total radiation calculated in that way, is given in table IX, together with the total radiation observed under the same conditions. The mean

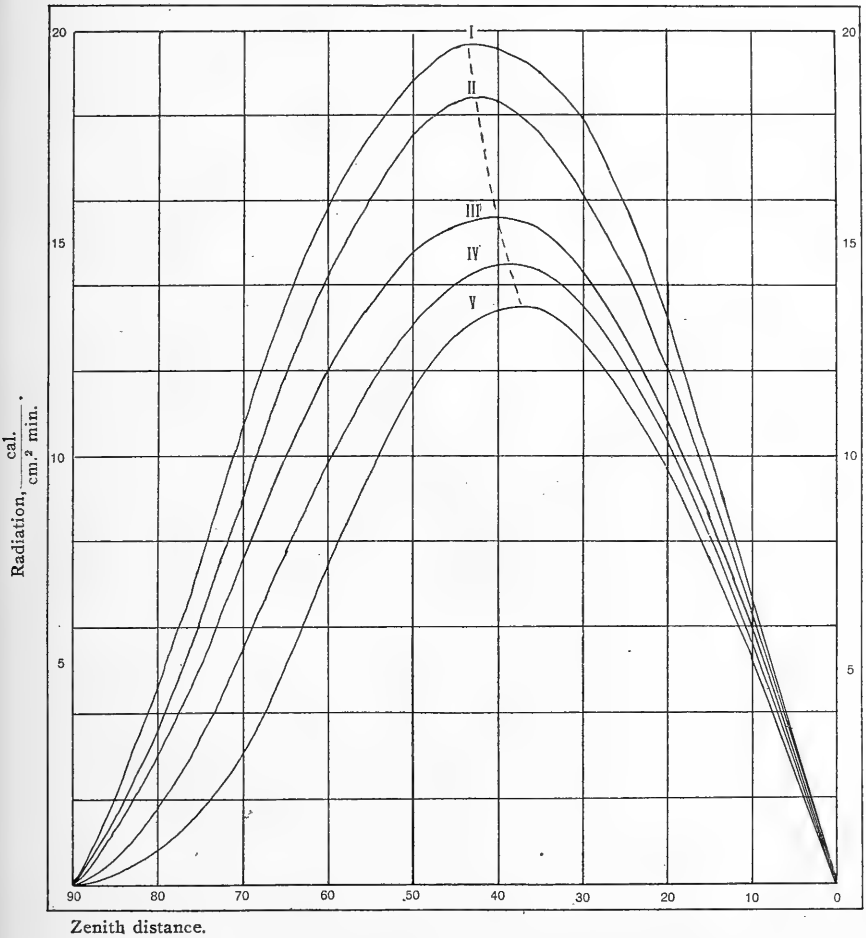

FIG. 12.—Radiation from horizontal surface to different parts of the sky.

difference between the two values is only 0.003, viz., less than 2 per cent. Considering the great difficulty of the observations upon which the computed value is based, the agreement must be regarded as very satisfactory. I therefore think we are justified in drawing therefrom the following conclusions:

I. That there is proportionality between the radiation and the energy of the current, used for compensation, down to very low values of both of them.

This is a very important point, as far as the utility of the instrument is concerned. The truth of the statement is clear from the fact that we can add up small portions observed and get a sum equal to the total quantity observed.

II. That the way in which the distribution curves have been extrapolated down to 90° zenith angle must be nearly correct.

III. That the sky must have been very uniform during the time of observation. If this had not been the case, it would not have been possible to calculate the total radiation from observations upon a single vertical circle.

From the diagrams it is to be concluded that the maximum of radiation from a horizontal surface toward rings of equal angular

Table X

Observer	0°–22°30′	22°30′–45°	45°–67°30′	67°30′–90°	p
Homén	1.00	0.93	0.87	0.61	...
Ångström 1[1]	1.00	0.98	0.90	0.74	1.5
Ångström 2[1]	1.00	0.98	0.88	0.67	3.6
Ångström 3[2]	1.00	0.94	0.86	0.60	3.8
Ångström 4[2]	0.99	0.92	0.75	0.41	5.0
Ångström 5[2]	0.97	0.91	0.65	0.23	7.1

[1] Mt. Whitney (4,420 m.). [2] Bassour (1,160 m.).

width takes place in a direction that makes an angle of between 35° and 45° with the zenith. An increase of the water-vapor density of the atmosphere shifts this maximum nearer the zenith; with decreasing density the maximum approaches a limiting position of 45°, which it would have if no absorbing and radiating atmosphere existed.

In table X, which is obtained by measuring the corresponding areas in figure 12, the ratios are given between the values of the radiation within various zones, obtained from the observations, and the same values as calculated from the simple sine-cosine law, that is, for the case where a horizontal surface radiates directly to a non-absorbing space. Hereby the radiation is assumed to be unity for zenith angle 0°. Between 80° and 90° the radiation is only between 0.5 per cent and 2.0 per cent of the total radiation. The influence

of mountain regions that do not rise higher than about 10 or 15 degrees above the horizon is therefore very small and can be neglected. In valley regions the effective radiation must be less than on a plane, owing to the shading influence of the mountains around. The conditions will, however, be slightly complicated through the superposed radiation from the surface of the mountains themselves, a radiation that is dependent upon the temperature of the heights and the properties of their surfaces (influence of snow).

CHAPTER VII

RADIATION BETWEEN THE SKY AND THE EARTH DURING THE DAYTIME

I must include here some observations which, in spite of their preliminary nature, yet may be of use in throwing a certain light upon questions nearly connected with the problem especially in view.

In the daytime, the radiation exchange between the sky and the earth is complicated by the diffuse sky radiation of short wave length that is present in addition to the temperature radiation of the sky. If this diffuse radiation is stronger than the effective temperature radiation to the sky, a black body like the instrument will receive heat. In the contrary case it will lose heat by radiation.

If one attempts to measure this positive (from sky to earth) or negative radiation with the instrument used in the present investigation, the sun itself being carefully screened off, such an attempt meets with the difficulty arising from the introduction of a systematic error. The bright metal strip has a smaller reflecting power for the diffuse radiation of short wave length than for the longer heat waves and we can no longer make use of the instrumental constant k, which holds only for long waves such as we have to deal with in the measurements of the nocturnal radiation. The reflecting power of the strips being about 97 per cent for waves longer than $2\,\mu$, and only about 70 per cent for waves of $0.5\,\mu$ length (a mean value of the wave length of the diffuse sky radiation), the introduction of the constant k into daylight measurements will evidently give a value of the sky radiation that is about 30 to 35 per cent too low.

On several occasions during the summer of 1912, I had the opportunity of making skylight measurements as well with my own instrument as with an instrument constructed on the same principle, but modified for the purpose of making day observations. This latter instrument is briefly described by Abbot and Fowle[1] in their interesting paper, "Volcanoes and Climate," where the effect of the diffusing power of the atmosphere on the climate is fully discussed. Both the strips employed in this instrument are blackened.

[1] Smithsonian Miscellaneous Collections, Vol. 60, No. 29, 1913. (Reprinted in Annals of the Astrophysical Observatory of the Smithsonian Institution, Vol. 3.)

Instead of being side by side, the strips are here placed one above the other beneath a thin horizontal plate of brass. When the instrument was in use, a blackened screen was placed beneath it, so that the lower strip was exchanging radiation only with this screen, which subtended a hemisphere. The upper strip was exchanging radiation with the whole sky. The radiation was calculated from the current necessary to heat the upper strip to the same temperature as the lower one.

Even in the use of this instrument in its original form, it is difficult to avoid some systematic errors. One is due to the difficulty of protecting the screen with which the lower strip exchanges radiation, from absorbing a small fraction of the incoming radiation and in this way giving rise to a heating of the lower strip. And secondly the convection is apt to be different, the effect of rising air currents being greater for the upper strip than for the lower one. The error introduced by these causes may possibly amount to 10 or 15 per cent. In this instrument as well as in the original Ångström instrument, the error, when we attempt to measure the sky radiation during the day, tends to make this radiation appear weaker than it really is.

TABLE XI—*Radiation of the Sky*

	Sept. 5	Sept. 6	Sept. 7	Mean
Before sunrise	—0.169	—0.205	—0.208	—0.194
Noon	+0.062	+0.092	+0.047	+0.067
After sunset	—0.208	—0.225	—0.220	—0.218
Total sky radiation	+0.250	+0.307	+0.261	+0.273

Table XI gives some results of observations with the last named instrument, taken by Dr. Abbot and the author. My measurements of the nocturnal radiation during the preceding and following nights are given in the same place. The total diffuse sky radiation is calculated on the assumption that the effective temperature radiation during the daytime is a mean of the morning and evening values determined by the nocturnal apparatus. The sky was perfectly uniform during the observations but was overcast by a faint yellow-tinted haze, ascribed by Abbot to the eruption of Mount Katmai in Alaska. The energy of the direct solar beam at noon was, for all three days, 1.24 to 1.25 cal. The sun's zenith angle at noon was 32°. From the table it may be seen that there was always an access of radiation from the sky, indicating that the diffuse radiation from the sky was always

stronger than the outgoing effective temperature radiation. The same was indicated by the nocturnal instrument, which, on two different occasions, showed, in one case no appreciable radiation in any direction, and in the other case a faint positive radiation from the sky. If we correct for the reflection of the bright strip the two instruments seem to be in general agreement with each other, showing the radiation from the sky to be *positive in the middle of the day,* under the conditions of the place. Lo Surdo found the same to be the case at Naples, where he observed during some summer days. On the other hand, Homén's observations at Lojosee in Finland, show that there the radiation during the daytime had the direction from earth to sky, and that consequently the effective temperature radiation was stronger (and very much stronger) than the incoming diffused light. The observations of the two observers are naturally in no way contradictory. The total radiation during the daytime is a function of many variables, which may differ largely from place to place. It is dependent on the effective temperature radiation to the sky. This radiation is probably about the same in different latitudes, a circumstance which will be discussed below; the effect of the higher temperature in low latitudes being counterbalanced by a high humidity. Thus we must seek the explanation in the behavior of the other important term, the scattered skylight. The strength of this light is dependent upon the diffusing power of the atmosphere: the molecular scattering and the scattering by dust, smoke, and other suspended particles in the air. For a not too low transmission of the air, the intensity of the skylight must increase with a decrease in the transmission power, so that the skylight is intense when the solar radiation is feeble, and vice versa.

There is nothing to indicate that the scattering power of the atmosphere is larger as a rule in low latitudes than at high ones, and I am therefore inclined to think that we ought not to ascribe the high intensity of the skylight in low latitudes to that cause. But the intensity of skylight is affected by another important factor—the height of the sun above the horizon. The nearer the sun approaches the zenith, the more intense must be the light reaching us from the diffusing atmosphere. The theory of scattered skylight, with due consideration of the so-called "self-illumination" of the sky, has been treated in a very interesting and remarkable paper by L. V. King.[1] In his paper King gives curves and equations representing

[1] Phil. Trans. Roy. Soc. London, Ser. A, Vol. 212, pp. 375-433.

the intensity of the scattered skylight as a function of the attenuation of the solar radiation and of the zenith distance of the sun. The theoretical result is not in exact agreement with the few observations that have been made, for instance, by Abbot and Fowle, which may be partly due to the difficulties in this kind of observation; but the theoretical consideration proves that the intensity of the skylight must be a decreasing function of the sun's zenith distance. For the same transmission coefficient of the atmosphere, the skylight must therefore be stronger, on an average, in low latitudes than in high ones.

Systematic observations on the intensity of skylight in its dependence on other conditions are almost entirely lacking. This is one of the most important problems in atmospheric optics, whose consequences deeply affect the questions of climate and of the effects of dust and haze and volcanic eruptions upon the temperature conditions of the earth. The publications of Nichols, Dorno, and especially those of Abbot and Fowle contain important contributions to the problem. The outlines for further investigations of the subject seem to me to be given by the theoretical considerations of King.

A question of special interest for the problem I have dealt with in my investigation is this: Is the temperature radiation of the atmosphere during the day the same as during the night, when temperature and humidity conditions are assumed to be the same, or will the atmosphere under the direct influence of the solar radiation assume properties which will result in a deviation from the conditions prevailing in the night-time as far as the radiation is concerned? This question ought to be treated in a general way by methods allowing us to eliminate the short wave radiation and to observe the temperature radiation during different times of the day. Here I will only give a brief account of some observations made during the total eclipse of the sun in 1914 and of conclusions to be drawn from them in regard to the last named question. The observations were carried out at Åviken, a place situated on the Swedish coast, on the central line of the total eclipse, during the two nights preceding and one night following the total eclipse and also during the eclipse itself. As I myself was engaged in other observations I had availed myself of the able assistance of Dr. G. Witt and of Mr. E. Welander of the Institute of Engineering, Stockholm, for carrying out these observations.

In order to protect the instrument from the direct sunlight, a screen arrangement was used, where the screen, through a simple

mechanical device, could be made to follow the changes in the position of the sun. The screen was blackened on the side turned towards the instrument and covered with white paper on the other side. The screen itself was to no appreciable degree heated by the sun radiation.

In figure 13 the observations are plotted as ordinates in a diagram where the time of the day is given by the abscissæ. The more the sunlight—and therefore also the scattered skylight—is cut off

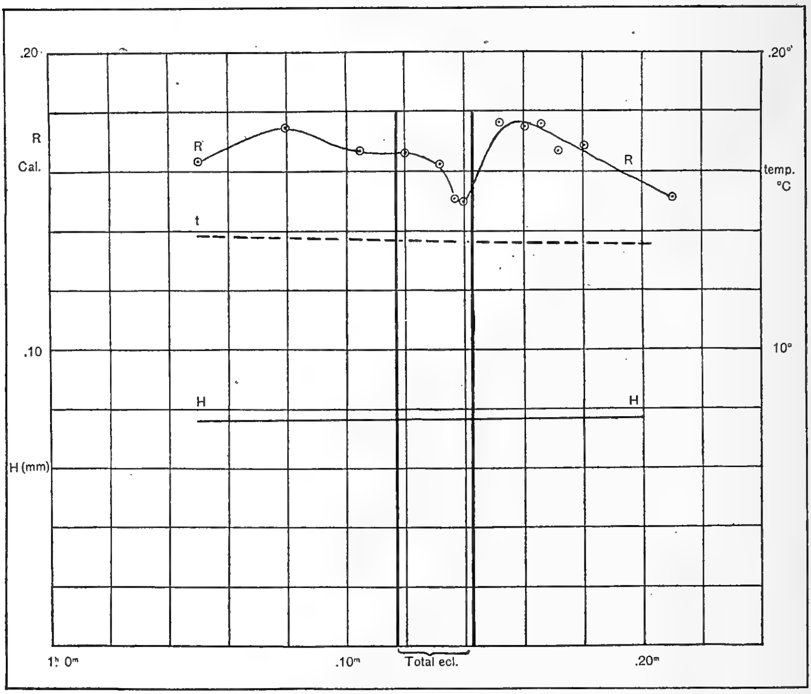

FIG. 13.—Radiation observed during total eclipse August 20, 1914.

by the shadowing body of the moon, the more the effective radiation to the sky naturally increases. From what has been said above it is clear that we are right in comparing the radiation during the total phase only, with the values obtained during the night. The feeble radiation from the corona is perfectly negligible and causes no complications. The mean radiation during the totality is found to be 0.160. At the same time the temperature of the surrounding air was 13.6°, the humidity as given by the Assmann psychrometer, 7.7 mm. A comparison between the value of the effective radiation during the

eclipse and the value given by night observations under the same temperature and humidity conditions, displays a very slight difference. I therefore think that one may conclude that the effective temperature radiation during the day follows the same laws as hold for the nocturnal radiation. More extensive investigations are however needed before this conclusion can be regarded as definite.

It is of interest to notice that during the whole time preceding the eclipse, the instrument showed an outgoing radiation to the sky. From the intensity of this radiation it can be concluded that, at least before noon, the temperature radiation to the sky must have been stronger than the diffuse radiation from it. The same was found by Homén to be the case at Lojosee in Finland, as has been indicated in the discussion above.

CHAPTER VIII

APPLICATIONS TO SOME METEOROLOGICAL PROBLEMS

A. NOCTURNAL RADIATION AT VARIOUS ALTITUDES

The number of investigations contributing to our knowledge of this special question is not large. When we have mentioned the simultaneous observations of Pernter[1] at Rauris and on Sonnblick, and the observations of Lo Surdo[2] at Naples and Vesuvius we have exhausted the previous work on this subject. The observations that have been described above seem now to give a basis for forming a general view upon the question of the influence of altitude upon the effective radiation. In several cases observations have been carried out simultaneously at different altitudes, but before we enter upon a comparison between them, we shall treat the subject in a more general way. As has been emphasized on several occasions, our observations indicate that the atmospheric radiation in the lower layers of the atmosphere is dependent chiefly on two variables: temperature and humidity. Hence it is obvious that if we know the temperature and the integral humidity as functions of the altitude, we can calculate the radiation of the atmosphere at different altitudes, provided that the relation between radiation, temperature, and humidity is also known. It has been the object of my previous investigations to find this relation; hence, if the temperature and humidity at the earth's surface are known, together with the temperature gradient and the humidity gradient, I can from these data calculate the radiation at different altitudes. The radiation of the atmosphere will evidently always decrease with increasing altitude. But the effective radiation, which is dependent also on the temperature of the radiating surface, will behave very differently under different conditions. If no radiating atmosphere existed, the effective radiation would decrease with a rise in altitude owing to the decreasing temperature. If the temperature of the atmosphere were constant, the effective radiation would always increase, when we moved to higher levels, owing to the fact that the atmosphere (which is now assumed to radiate) gets thinner the higher the altitude.

[1] *Loc. cit.* (Histor. Survey).
[2] Nuovo Cimento, 1900.

In order to get a general idea of the conditions, I will assume that Süring's formula:

$$e_h = e_0 \cdot e^{-\frac{h}{2606}\left(1+\frac{h}{20}\right)}$$

holds for the distribution of the humidity, and that the temperature gradient is constant up to an altitude of 5,000 m. I will consider the following special cases:

I The temperature gradient is 0.8° per 100 meters.
II " " " " 0.6° " " "

The pressure of the aqueous vapor at the earth's surface is: (a) 5 mm.; (b) 10 mm.; (c) 15 mm.

The effective radiation R_t at different altitudes can then be calculated according to the formula:

$$R_t = T^4 \cdot 0.170\,[1 + 1.26 \cdot e^{-0.069\rho}] \cdot 10^{-10}$$

where ρ can be obtained from Süring's formula, and where e_h has to be corrected for the conditions pointed out in chapter V, B, of this paper. In table XIIA are given, (1) the temperature (t), (2)

TABLE XIIA—*Radiation at Different Altitudes*

Altitude	t	e_h'	e_h''	e_h'''	ρ'	ρ''	ρ'''	R'	R''	R'''
0	25°	5.0	10.0	15.0	5.5	11.0	16.6	0.205	0.164	0.146
1000	17°	3.35	6.7	10.0	3.4	6.8	10.1	0.208	0.171	0.150
2000	9°	2.15	4.3	6.45	2.05	4.1	6.1	0.205	0.177	0.167
3000	1°	1.35	2.7	4.05	1.3	2.4	3.6	0.195	0.178	0.165
4000	— 7°	0.77	1.55	2.3	0.7	1.2	1.8	0.182	0.175	0.166
5000	—15°	0.46	0.91	1.4	0.34	0.67	1.0	0.166	0.161	0.158

TABLE XIIB—*Radiation at Different Altitudes*

Altitude	t	e_h'	e_h''	e_h'''	ρ'	ρ''	ρ'''	R'	R''	R'''
0	25°	5.0	10.0	15.0	5.5	11.0	16.6	0.205	0.166	0.146
1000	19°	3.35	6.7	10.0	3.35	6.7	10.0	0.212	0.176	0.155
2000	13°	2.15	4.3	6.45	1.9	3.8	5.8	0.219	0.192	0.180
3000	7°	1.35	2.7	4.05	1.1	2.2	3.2	0.215	0.197	0.183
4000	1°	0.77	1.55	2.3	0.55	1.0	1.6	0.208	0.200	0.190
5000	—5°	0.46	0.91	1.4	0.28	0.55	0.8	0.194	0.190	0.185

the pressure of aqueous vapor (e_h), (3) the corrected pressure (ρ) and, finally, the effective radiation (R) at different altitudes. In table XIIB the same quantities are given for a temperature gradient of 0.6° per 100 meters. Figure 14 gives the curves, drawn from

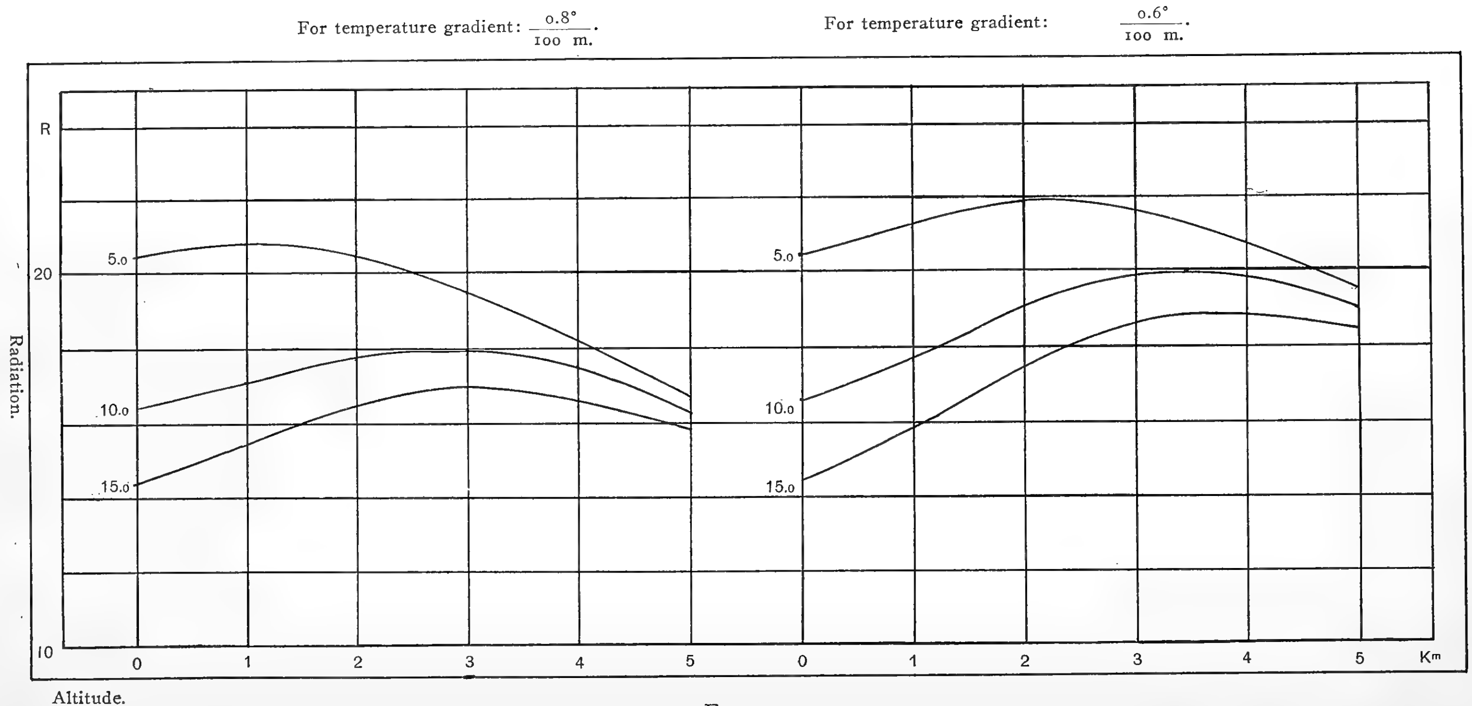
For temperature gradient: $\frac{0.8^\circ}{100 \text{ m.}}$.
For temperature gradient: $\frac{0.6^\circ}{100 \text{ m.}}$.
R
20
10
Radiation.
5.0
10.0
15.0
0
1
2
3
4
5
Km
Altitude.

FIG. 14.

the computed data, for the effective radiation as a function of the altitude. The curves bring out some interesting facts that deserve special consideration.

For ordinary values of the humidity, the effective radiation has a maximum at 1 to 4 km. altitude.

An increase of the humidity or a decrease of the temperature gradient shifts this maximum to higher altitudes.

The effective radiation gradient is consequently positive at low altitudes and negative at high altitudes.

An examination of the observations, made simultaneously at different altitudes, must naturally give a result that is in general accordance with these considerations, which are based upon the experimental investigations.

TABLE XIIIA

Date	Δt	Lone Pine			L. P. Canyon			Mt. Whitney		
		t	H	R	t	H	R	t	H	R
Aug. 2	0.61	18.3	10.0	0.141	....	...	.....	—1.3	3.2	0.182
3	0.57	17.6	8.0	0.166	....	...	.....	—0.7	2.7	0.182
4x	0.48	15.8	7.8	0.171	17.0	5.0	0.203	+0.6	2.4	0.196
5x	0.52	17.5	6.3	0.191	17.3	3.7	0.212	+1.0	2.1	0.188
8	....	....	....	.....	15.1	7.0	0.177	—1.4	3.5	0.166
9x	0.59	15.6	7.7	0.154	12.4	5.8	0.164	—3.4	3.0	0.154
10	....	18.7	7.7	0.185	11.4	6.1	0.168	.....	...	...
11	0.58	15.9	5.9	0.189	....	...	.....	—2.5	1.2	0.191
12	0.71	21.2	5.1	0.198	....	...	.....	—1.4	1.2	0.193
General mean	0.58	17.6	7.3	0.175	14.6	5.5	0.185	—1.1	2.4	0.182
Mean of (x)	0.53	16.3	7.3	0.172	15.6	4.8	0.193	—0.6	2.5	0.179

TABLE XIIIB

Date	Δt	Indio [0 m.]			Mt. San Gorgonio [3,500]					
		t	H	R	t	H	R			
July 22	....	26.0	12.1	0.134	...	...	.....	...	...	...
23x	0.69	24.7	11.0	0.181	0.7	2.5	0.208	...	...	...
24x	0.61	23.5	9.6	0.172	2.1	1.6	0.217	...	...	...
Mean of (x)	0.65	24.1	10.3	0.177	1.4	2.1	0.213	...	...	...

In table XIIIA I have collected the data, gained simultaneously at different altitudes during the Mount Whitney expedition. The values represent mean values during entire nights. They confirm the fact, already deduced from more general considerations, that

the effective radiation has a maximum at an altitude of between 1,000 and 4,000 meters. Between 2,500 and 4,400 meters the mean gradient is generally negative; between 1,200 and 2,500 meters it generally has a positive sign. From the general discussion and the curves that represent ideal cases it is probable that the effective radiation always decreases with an increase in altitude, when about 3,000 meters is exceeded. Up to that altitude we shall generally find an increase of the effective radiation with the height. The latter conditions are demonstrated by my simultaneous observations at Indio and Mount San Gorgonio (table XIIIB), as well as by Pernter's[1] observations at Rauris and on the top of Sonnblick.

B. INFLUENCE OF HAZE AND ATMOSPHERIC DUST UPON THE NOCTURNAL RADIATION

From the observations made in Algeria, the conclusion was drawn[2] that a slight haziness, indicated by a decrease in the transmission by the atmosphere of visible rays (clouds not formed), had no appreciable influence upon the radiation of the atmosphere. In fact it was found from pyrheliometric measurements during the day that the transmission of the atmosphere generally kept a high or low or average value during periods of several days, the changes being slow and continuous from one extreme to the other. The assumption being made that the nights falling between days of a certain value of transmission can be classified as showing the same character as the days, it was found that the nocturnal mean radiation during nights belonging to a period of high transmission only differed within the limits of probable error from the mean value obtained during low transmission periods.[3]

The observations at Bassour, Algeria, were taken at a time when the volcanic dust from the eruption of Mt. Katmai at Alaska caused a considerable decrease in the sun radiation transmitted to the surface of the earth. Several observers, such as Hellmann,[4] Abbot and Fowle,[5] Kimball,[6] Jensen,[7] and others, all agree as regards the prob-

[1] Pernter, *loc. cit.*

[2] A. Ångström: Studies in Nocturnal Radiation, I. Astroph. Journ., June, 1913.

[3] Abbot and Fowle: Volcanoes and Climate, l. c., p. 13.

[4] Zeitschrift für Meteorologie, Januari, 1913.

[5] Volcanoes and Climate. Smithsonian Misc. Collections, Vol. 60, No. 29.

[6] Bulletin of the Mount Weather Observatory, Vol. 3, Part 2.

[7] S. A. Mitt. d. Vereinigung von Freunden d. Astronomie und kosm. Physik, 1913.

able cause of this remarkable haziness. As regards the atmospheric conditions at Bassour, I may quote the description given by Abbot and Fowle in their interesting paper, Volcanoes and Climate: "On June 19 Mr. Abbot began to notice in Bassour streaks resembling smoke lying along the horizon, as if there were a forest fire in the neighborhood of the station. These streaks continued all summer, and were very marked before sunrise and after sunset, covering the sky towards the sun nearly to the zenith. After a few days the sky became mottled, especially near the sun. The appearance was like that of the so-called mackerel sky, although there were absolutely no clouds. In the months of July, August, and so long as the expedition remained in September, the sky was very hazy, and it was found that the intensity of the radiation of the sun was greatly decreased by uncommonly great haziness." Abbot and Dorno [1] both agree as to the average decrease per cent in the solar radiation caused by the dust; it was found to be about 20 per cent. "In the ultra-violet and visible spectrum the effect was almost uniform for all wave lengths, but was somewhat less in the infra-red." (Volcanoes and Climate.)

It is of very great interest to consider, in connection with the observations named, the effect of volcanic dust upon the *nocturnal radiation*. Unfortunately the observations at Algeria were not begun until after the haze had reached a considerable density, and therefore we cannot compare observations taken at the same place before and during the dust period. But the observations taken at Lone Pine during the California expedition may furnish a reliable basis for comparison, the two stations having almost exactly the same altitude. If we therefore consider the curve giving the relation between radiation and humidity at Lone Pine in comparison with the same curve obtained at Bassour, both curves reduced to the same temperature, we may from this draw some conclusions in regard to the effect of the volcanic haze. These curves are given in figure 5, and we can from the diagram read off the departures of the Lone Pine curve from the curve taken at Bassour. These departures are given in the following table, together with the mean departure, which is found to be $+0.003$ or just about 2 per cent of the mean radiation. The Lone Pine values are, on an average, a little less than 2 per cent higher than the values obtained at Bassour under identical conditions. If we compare the radiation values at Indio with those at Bassour in the same way, we shall find a departure of $+\frac{1}{2}$ per cent in favor of

[1] Met. Zt., 29, 1912.

the Indio values. One may conclude from this that the volcanic dust, which causes a decrease of about 40 per cent (Dorno) in the ultra-violet radiation and about 20 per cent in the visible affects the rays

Effective Radiation

ρ mm.	Lone Pine–Bassour
4	—0.004
5	+0.005
6	+0.012
7	+0.015
8	+0.009
9	—0.003
10, 11	—0.013
Mean	+0.003

that constitute the nocturnal radiation less than 2 per cent. As the nocturnal radiation has probably its maximum of energy in a region of wave lengths at about 8 μ, this is a fact that in itself is not very astonishing. Measurements in the sun's energy spectrum show that even for waves not longer than about 0.8 μ, the transmission of the atmosphere is very nearly equal to unity, the rays being very slightly affected by changes in the scattering power of the air. If we use the observations of Abbot or of Dorno in regard to the weakening of the ultra-violet and visible light, and apply the law of Rayleigh for the relation between scattering and wave length, we find from these data, applied to the average wave lengths of the regions concerned, that about 97 per cent of the radiation at 8 μ must pass undisturbed by the dust particles. There are several objections against a quantitative application of the theory of Rayleigh to the conditions here considered, but at least it shows that our result cannot be regarded as unexpected.

The fact that the nocturnal radiation has only decreased by about 2 per cent, when on the other hand the incoming solar radiation is reduced to about 80 per cent of its former value, explains the interesting relation between climate and volcanic eruptions pointed out by Abbot and Fowle in their paper already referred to. That the climatic effect is not larger, in spite of the great decrease in the insolation, may be due to the large number of processes at work—so to say—tending to balance or to weaken the consequences of a decrease in the incoming radiation. It has been shown here that this decrease is not to any appreciable amount counterbalanced by a decrease in the outgoing radiation from the *surface of earth*. But there are other

means by which heat is carried away from the surface, evaporation, and especially convection, being factors that are not negligible. It is probable that if a part of the solar radiation is really absorbed by the volcanic dust, this will tend to diminish the temperature gradient between the sea level and the upper strata of the atmosphere, and consequently cause a decrease in the vertical heat convection from the lower stations. A second *access* of radiation is due to the scattered skylight, and Abbot as well as Dorno point out that the sum of skylight and direct solar radiation was subjected to only a relatively small change by the effect of the dust. One has naturally to expect that if a part of the direct solar radiation is uniformly scattered by the atmosphere, a part of the scattered radiation will reach the surface of the earth in the form of skylight, this part increasing with an increase in the scattering power. Part of the scattered radiation is reflected out to space. Similar conditions naturally hold for the nocturnal radiation, and it is evident that the quantity measured by the instrument will always be the outgoing heat radiation diminished by the part of this radiation that is reflected back by the diffusing atmosphere upon the radiating surface.

C. RADIATION FROM LARGE WATER SURFACES

The radiation from bodies with reflecting but not absorbing or diffusing surfaces depends upon their reflecting power and their temperature only. The emission of radiation in a direction that makes an angle ϕ with the normal to the surface at the point considered, is determined by the relation:

$$E_\phi = \epsilon_\phi (1 - R_\phi)$$

where ϵ_ϕ is the radiation of a black surface in the direction ϕ, and R_ϕ the reflected fraction of the light incident in the named direction. For the total radiation emitted we have

$$E_\phi = \int \epsilon_\phi (1 - R_\phi) \, d\Omega$$

where the integration is to be extended over the whole hemisphere.

In chapter VI, I have given an account of some observations that show in what way the radiation from a black surface to the sky is dependent on the direction. As a very large part of the earth's surface is covered with water, and therefore slightly different from the conditions defined by the "black surface," I have thought it to be of interest to give here a brief discussion of the case where we have, instead of the black surface, a plane water surface radiating out to

space. The problem is important for the knowledge of the loss of heat from the oceans, and would probably be worth a special investigation in connection with an elaborate discussion of the quantity of heat absorbed from the incoming sun and sky radiation by water surfaces. Here I propose only to give a short preliminary survey of the question, giving at the same time the general outlines of the probable conditions.

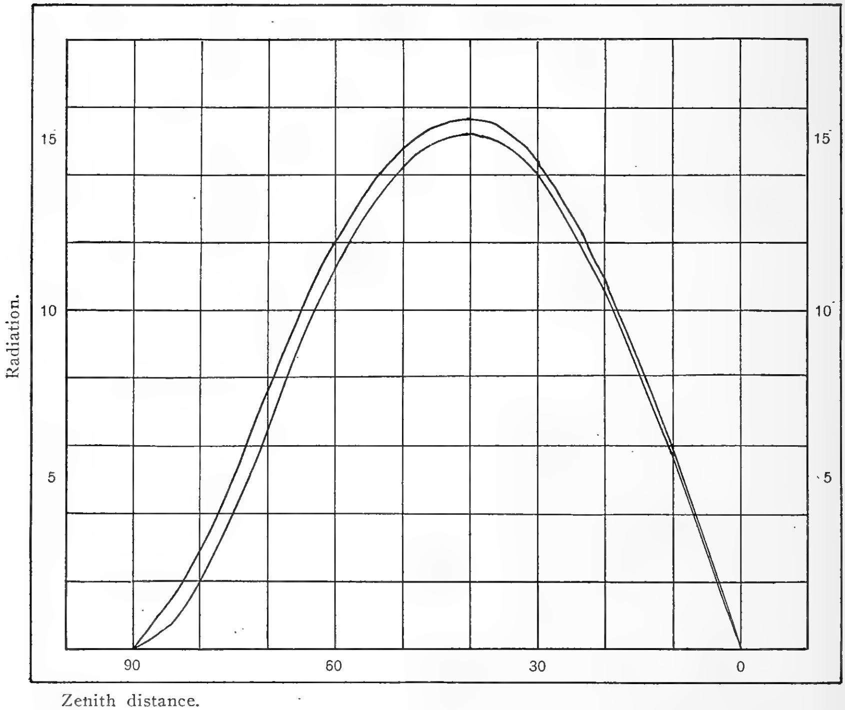

FIG. 15.—Radiation from water surface to sky. Lower curve for water surface. Upper curve for perfect radiator. From Bassour observations ($\rho = 5$ mm.). Ratio of areas 0.937.

In figure 12 I have given some curves representing the relative radiation from a black surface in various directions toward rings of equal angular width. The total energy emitted is represented by the areas of these curves. Now, if every ordinate is multiplied by the factor $(1 - R_\phi)$, where R_ϕ can be obtained from Fresnel's formulæ, if we know the index of refraction, the area included by the new curve will give us the radiation emitted by a water surface under the same conditions of temperature and water-vapor pressure. In figure 15 such curves are given. I have here assumed the mean refrac-

tive index for the long waves here considered to be 1.33, a value that is based upon measurements by Rubens and myself. The upper curve is taken from figure 12, curve IV. This same curve corresponds to a water-vapor pressure of 5 mm. The ratio between the areas is 0.937, *i. e.*, the water surface radiates under the given conditions 93.7 per cent of the radiation from a black body. A change in the water-vapor pressure will affect this ratio only to a small extent.

I will now assume that a black horizontal surface radiates to space, and that the vertical distribution of the water vapor over the surface satisfies the conditions for which our radiation formula holds (Chapter III (2)). Then the radiation can be computed provided the tem-

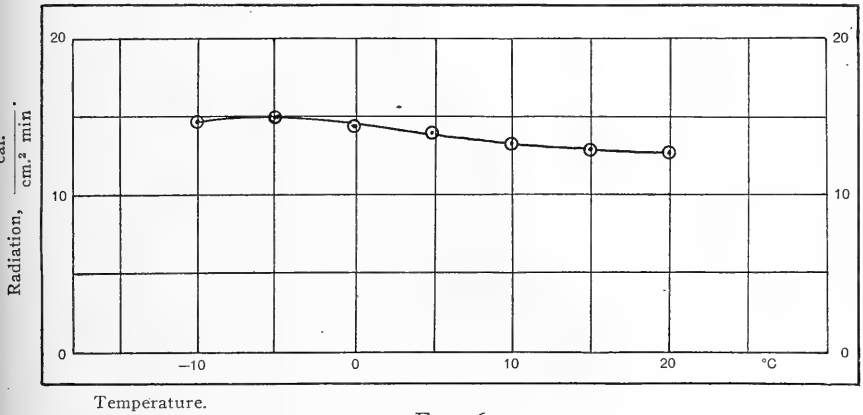

FIG. 16.

perature is known. If the black surface is replaced by a water surface the radiation will be only 94 per cent of its former value. The latter radiation is given as a function of the temperature by figure 16, where I have applied the considerations made above to the interval between $-10°$ C. and $+20°$ C. From the figure may be seen how the radiation is kept almost constant through the increase with rising temperature of the water-vapor content of the atmosphere. There is only a slight *decrease* in the radiation *with rising temperature.*

The ideal conditions here imagined are probably more or less inconsistent with the actual state of things. In the first place, the air immediately above the ocean is generally not saturated with water vapor, the relative humidity being rarely more than about 90 per cent. In the second place, it is not quite correct to assume that the average distribution of the water vapor over the ocean is the same as the

average distribution over land. This will give a deviation from the assumed conditions and consequently a different absolute value to the radiation, but it will probably only to a small extent change the relative values and the general form of the curve.

Melloni[1] concludes his first memoir on the cooling of bodies exposed to the sky, published about 70 years ago, with the following remarkable statement, upon which he seems to lay a certain stress: " . . . . Un corps exposé pendant la nuit à l'action d'un ciel également pur et serein se refroidit toujours de la même quantité quelle que soit la température de l'air."

One may at first be inclined to attach very little importance to this statement. It seems in fact to be in contradiction with the most elementary laws of radiation. If we consider the temperature of the radiating surface as the only variable upon which the radiation depends, we would expect the cooling of the body below the temperature of the surroundings to be proportional to the fourth power of its absolute temperature. At 0° C. the cooling would for instance be only about three fourths as much as at 20° C.

Now the effect of temperature is generally a double one, as far as the radiation process is concerned. With a rise in temperature there generally follows an increase in the absolute humidity, which causes an increase in the radiating power of the atmosphere. The increase of the temperature radiation from the radiating surface is balanced by a corresponding increase in the radiation of the atmosphere; and the observed effective radiation is therefore only subjected to a small variation. The observations, discussed in previous chapters, seem now to indicate that the law of Melloni is *approximately* true with the following modification:

The cooling of a body, exposed to radiate to a clear night sky, is almost independent of the temperature of the surroundings, *provided that the relative humidity keeps a constant value.*

This conclusion, which can be drawn from the observations on the influence of humidity and temperature on the effective radiation, must be regarded as remarkable. It includes another consequence, namely, that a high incoming radiation (sky and sun) and a therefrom resulting tendency to an increase of the temperature, is generally *not* counterbalanced by a corresponding increase in the effective radiation from the surface of the earth to space. The variations of the incoming radiation are therefore, under constant temperature conditions, almost entirely counterbalanced by variations in convection, and evaporation (or other changes) of water.

[1] Melloni, *loc. cit.* (chapter II).

CONCLUDING REMARKS

In this " Study of the Radiation of the Atmosphere," I have attempted an investigation of the influence of various factors—humidity, temperature, haze, clouds—upon the radiation of the atmosphere. The results of these investigations are briefly summarized at the beginning of the paper.

It may be of advantage here to state in a few words in what respects this study must be regarded as incomplete and in need of further extended investigations. In the first place, it will be noticed that my observations have been limited to a particular time of year; the observations in Algeria and in California have all been made during the periods July-August of the years 1912 and 1913.

Now the investigations, as yet unpublished, carried on at the Physical Institute of Upsala, indicate that the amount of ozone contained in the atmosphere is larger in winter time than in summer time. Further, it has been shown by K. Ångström[1] that the ozone has two strong absorption bands, the one at $\lambda=4.8\,\mu$, the other at $\lambda=9.1$ to $10\,\mu$, of which the latter especially is situated in a region of the spectrum where the radiation of a black body of the temperature of the atmosphere ought to have its maximum of radiation. Then it is obvious that the radiation of the atmosphere must be dependent also upon the quantity of ozone present. Spectroscopic investigations indicate that in the summer time the ozone present in the air is practically nil; it is therefore not liable to have introduced any complications into the results discussed in this paper. But in the winter the quantity of ozone is often considerable, and it is not impossible that the variations of the effective radiation in the winter may be partly due to variations in the quantity of ozone in the upper air layers. The consequence of the higher radiating power of the atmosphere, due to the presence of ozone, must be that the effective radiation ought to be found to be less in the winter than is to be expected from the observations discussed in this paper.

Another point where it is desirable that the observations of the " nocturnal radiation " should be extended, is in regard to conditions under which the quantity of water in the air is very small. Such

[1] K. Ångström: Arkiv für Mat., Astr. och Fysik I, p. 347, 1904. *Ibidem,* I, p. 395, 1904.

observations will not only be more directly comparable with the observations on high mountains than those used here for such a comparison, but they will also furnish a basis for studying the variations in a dry atmosphere and the influences by which these variations are affected. Further, the study of the radiation of the upper air layers is as yet very incomplete and ought to be extended by means of continuous observations on high mountains or, perhaps better, from balloons. My observations indicate that the " perfectly dry atmosphere " has a radiating power as great as 50 per cent of the radiation of a black body at the temperature of the place of observation. The upper air layers—the stratosphere—must therefore have a considerable influence upon the heat economy of the earth as a whole. Observations at high altitudes of the absorption and radiation of the atmosphere are therefore very desirable.

Finally, means must be found to study the effective radiation during the daytime in a more systematic way than has been done in this paper. The effective temperature radiation—that is, the difference between the total effective radiation and the access of scattered skylight—can evidently be obtained by measuring these two last named quantities simultaneously; measurements that do not seem to involve insurmountable difficulties.

EXPLANATION OF FIGURES 17 TO 25

The figures give the effective radiation in $\frac{\text{cal.}}{\text{cm.}^2\ \text{min.}} \cdot 10^2$, plotted as ordinates against the time (in hours of the night) as abscissæ. The curves are governed by the observations given in several of the tables, XIV to XX. For the graphical interpretation I have chosen some of the observations that seem to me to bring forward, in a marked and evident way, the influence of humidity or temperature upon the radiation. They therefore represent cases where either the temperature has been almost constant (as on high mountains), and the humidity subjected to variations, or where the humidity has been constant and the temperature has varied.

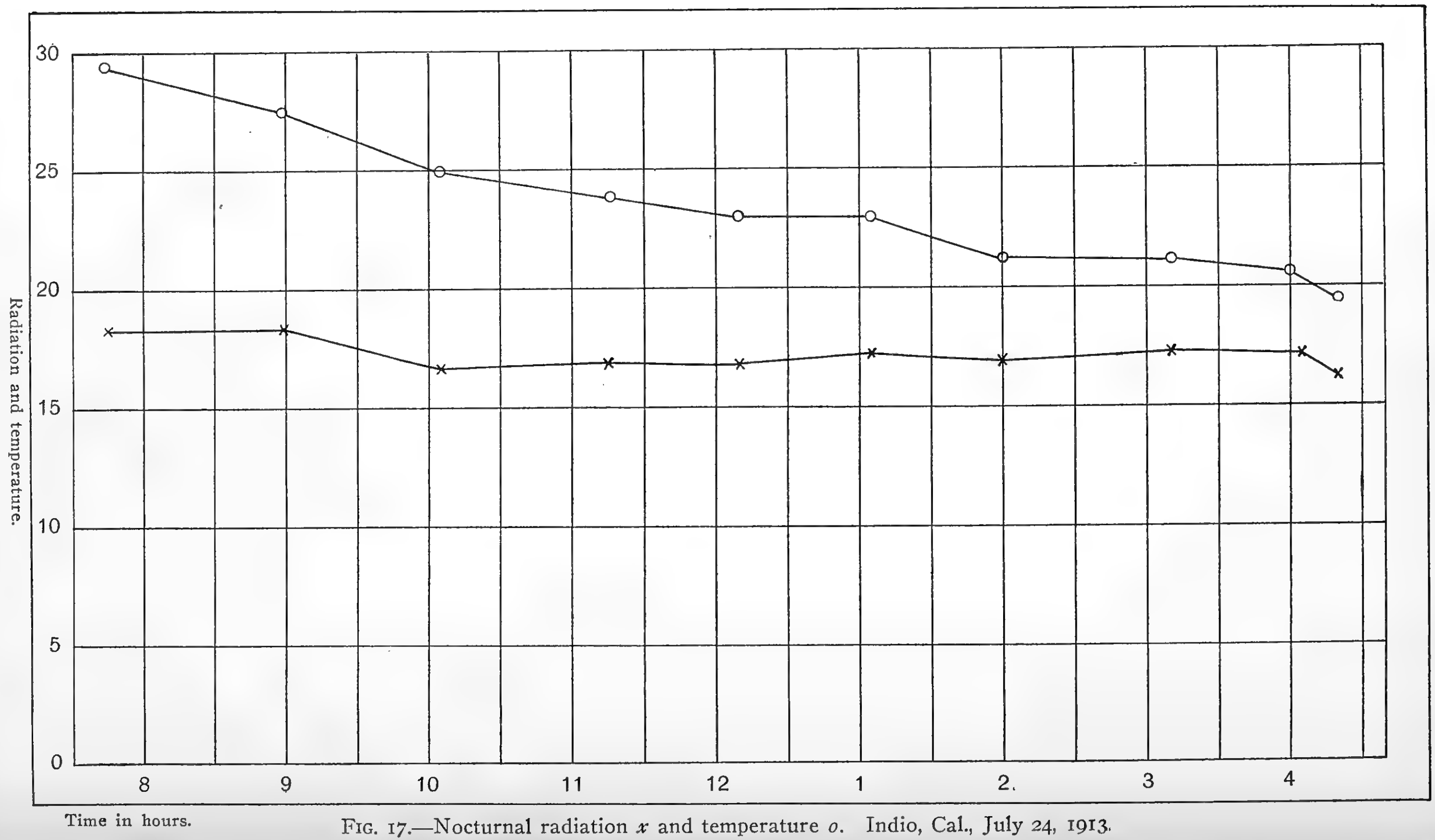

FIG. 17.—Nocturnal radiation x and temperature o. Indio, Cal., July 24, 1913.

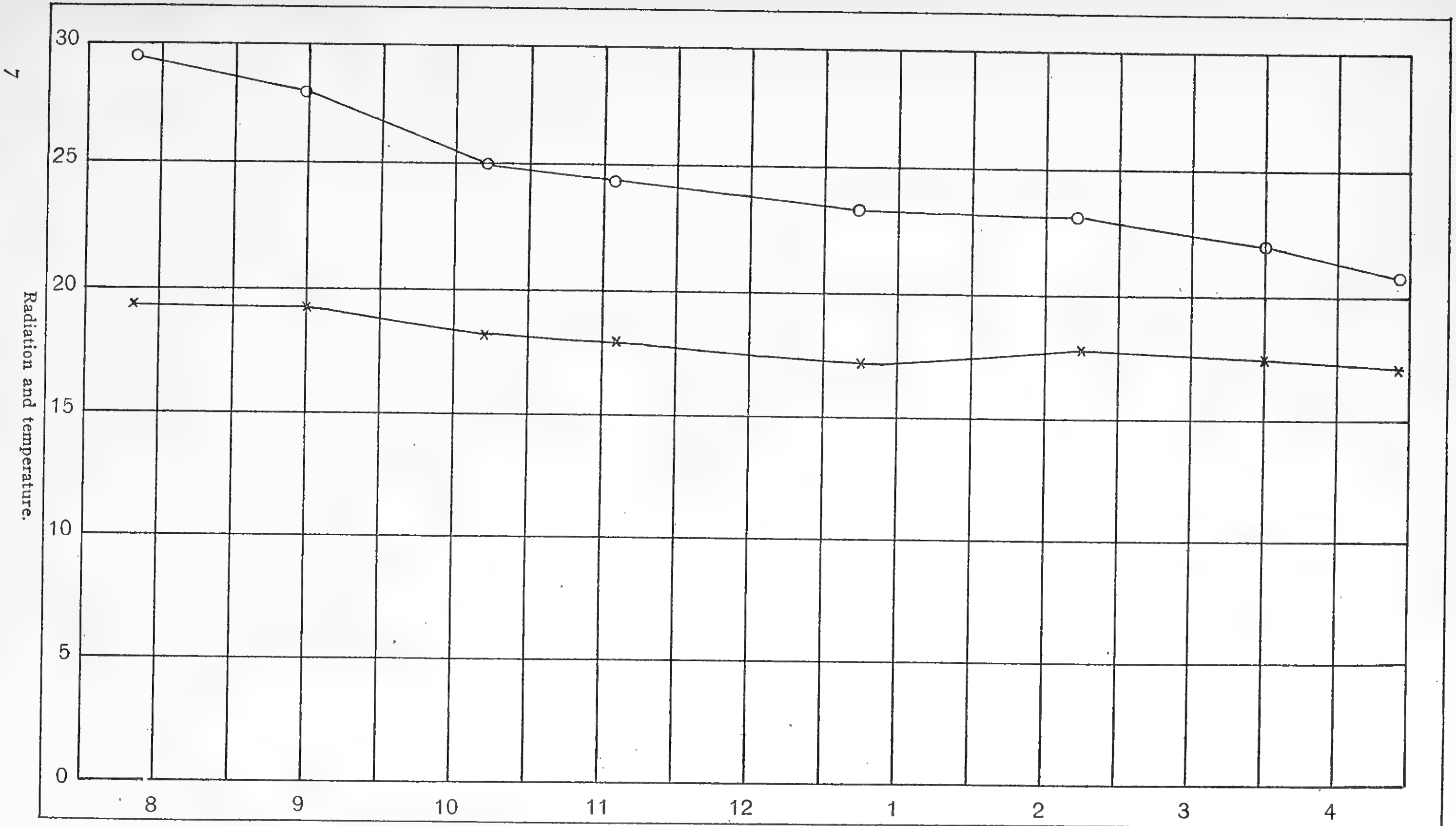

FIG. 18.—Nocturnal radiation x and temperature o. Indio, Cal., July 23, 1913

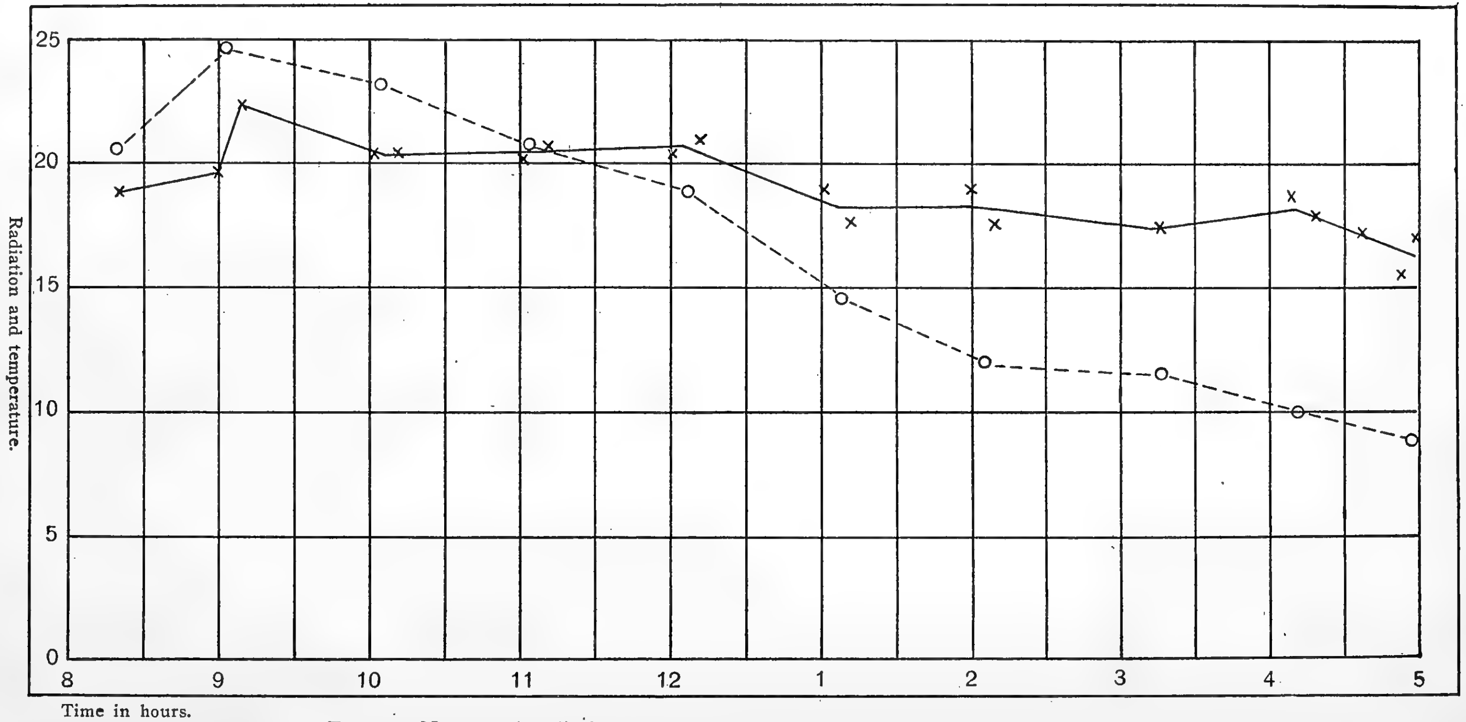

FIG. 19.—Nocturnal radiation x and temperature o. Lone Pine, Cal., August 11, 1913.

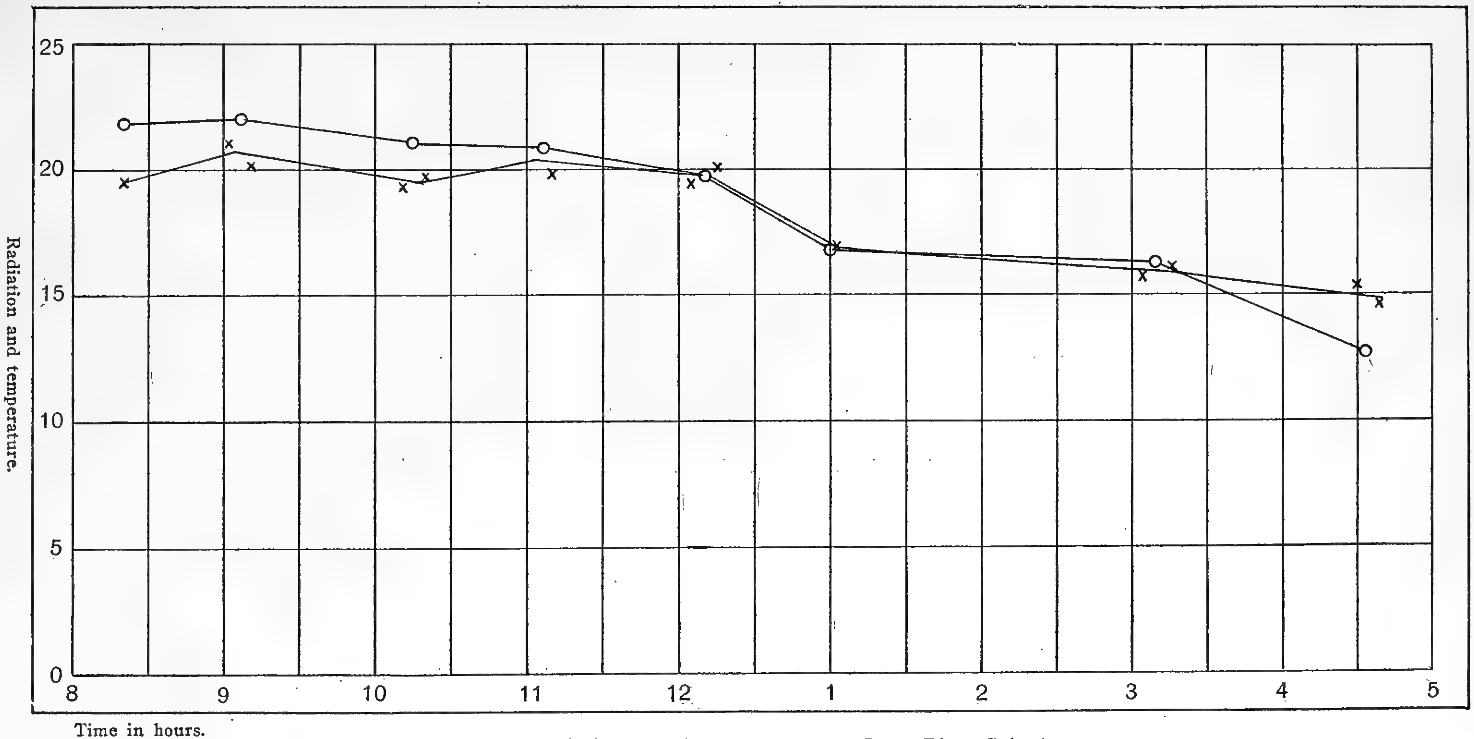

FIG. 20.—Nocturnal radiation *x* and temperature *o*. Lone Pine, Cal., August 10, 1913.

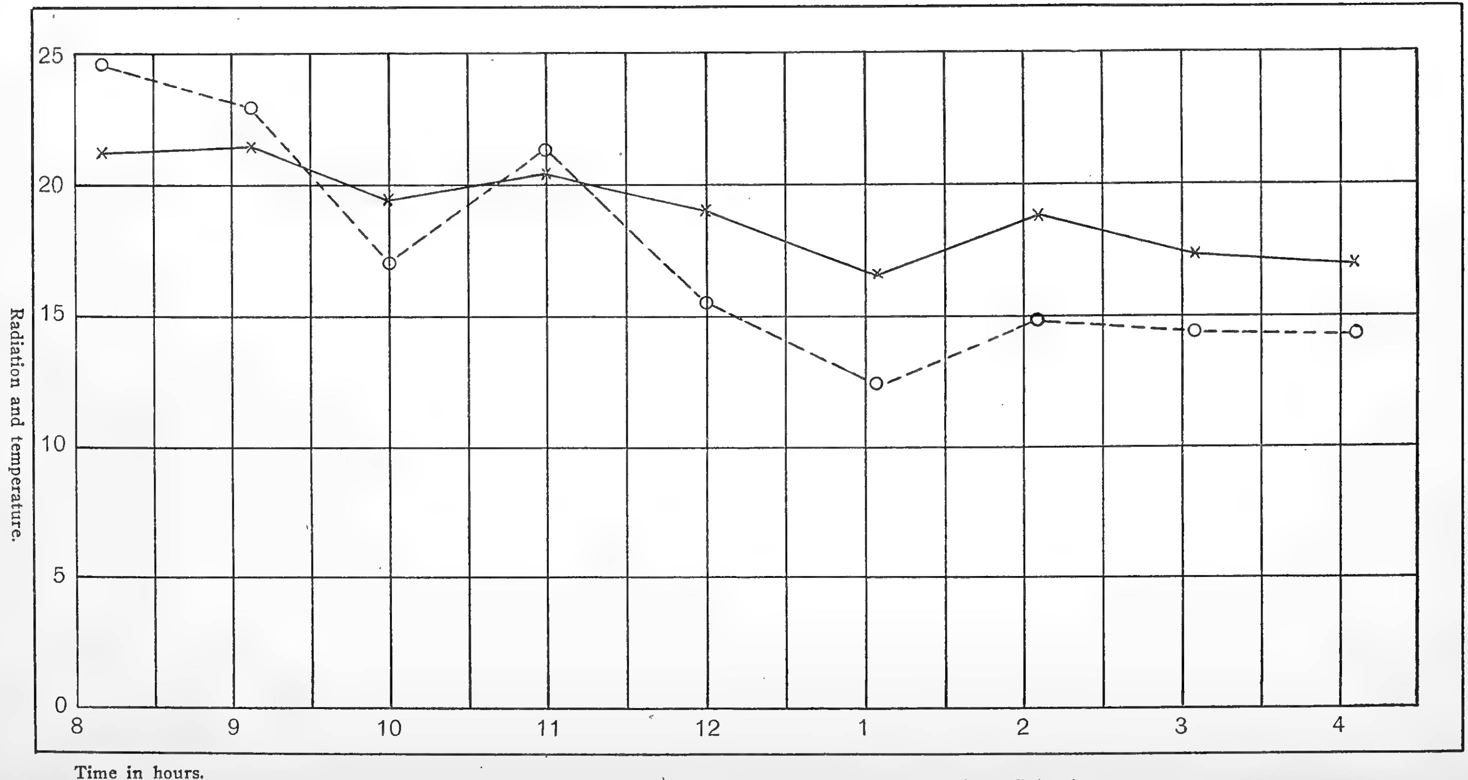

FIG. 21.—Nocturnal radiation x and temperature o. Lone Pine, Cal., August 5, 1913.

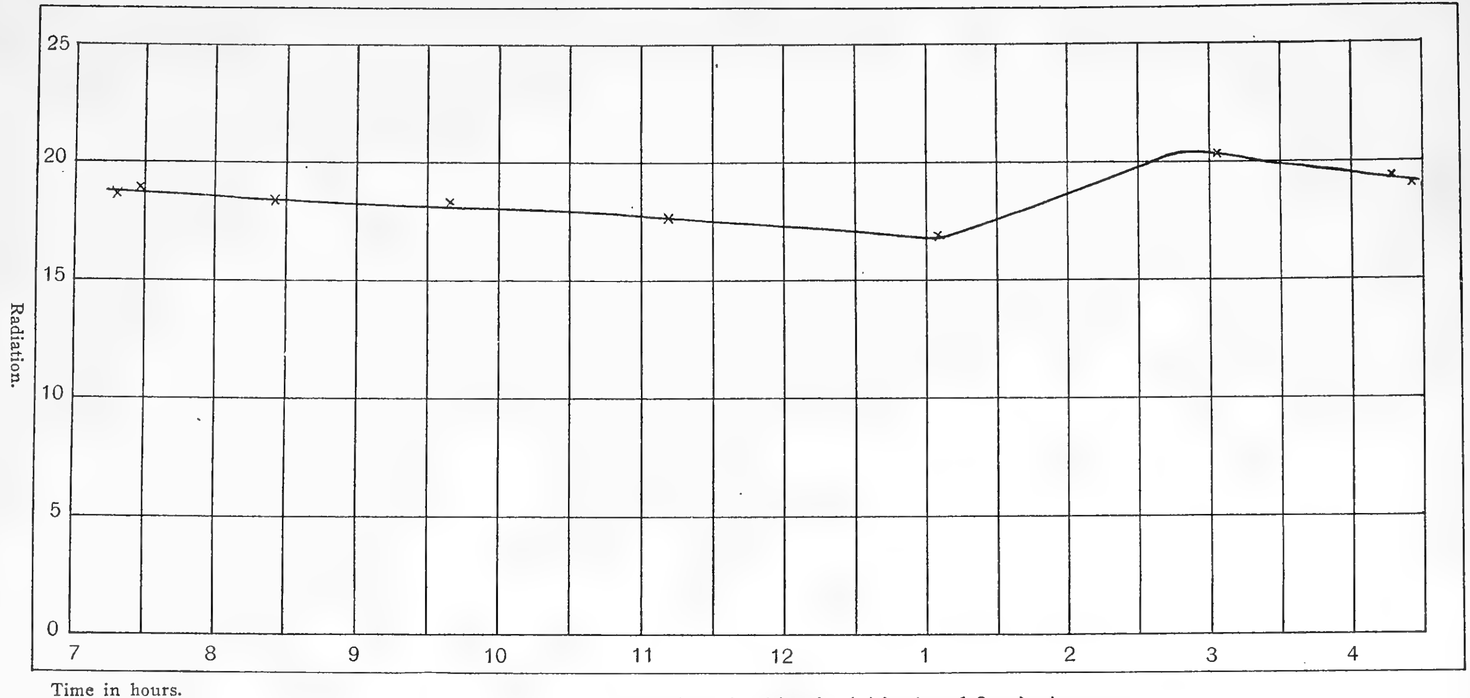

FIG. 22.—Nocturnal radiation. Mt. Mouzaia, Algeria (altitude 1,608 m.), August 27, 1912.

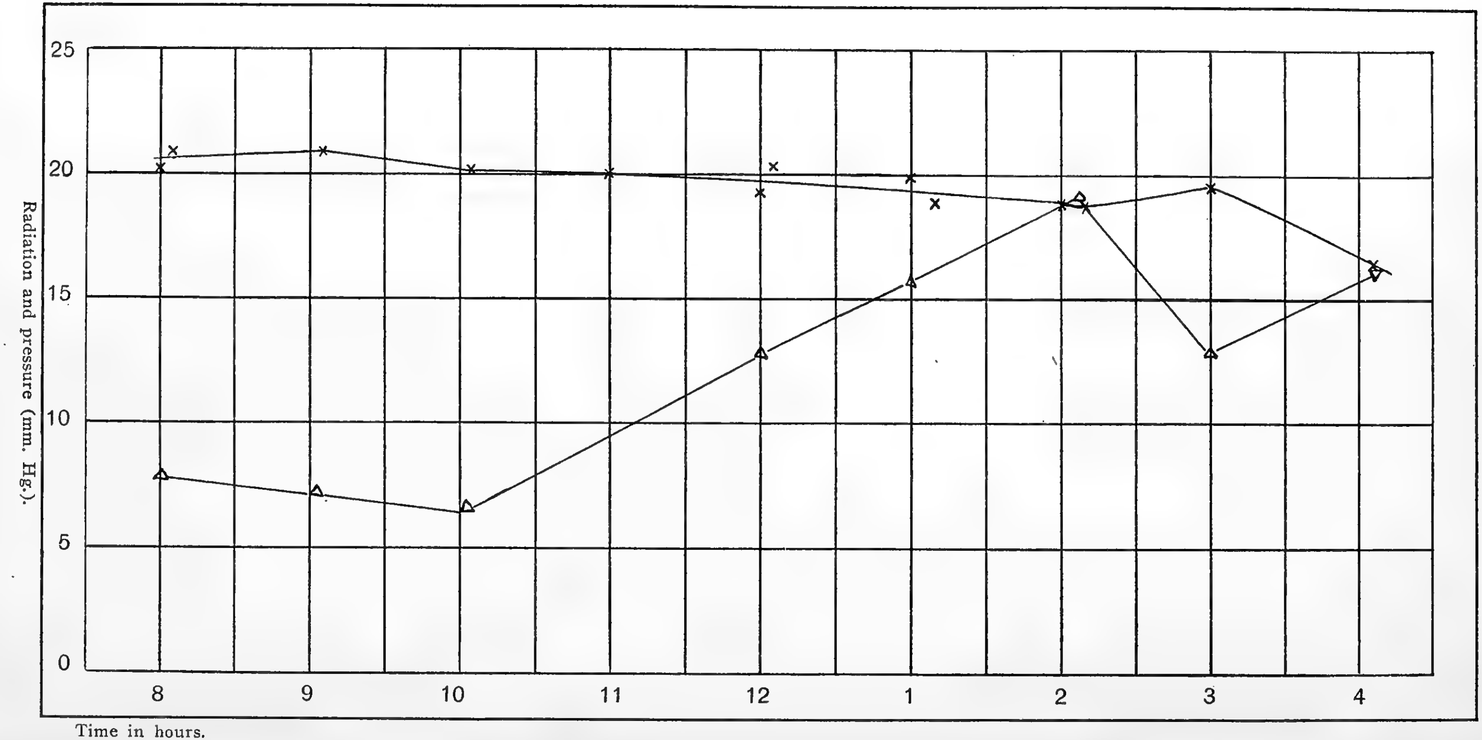

FIG. 23.—Nocturnal radiation x and water-vapor pressure Δ. Mt. San Antonio, Cal. (altitude 2,500 m.), July 12, 1913.

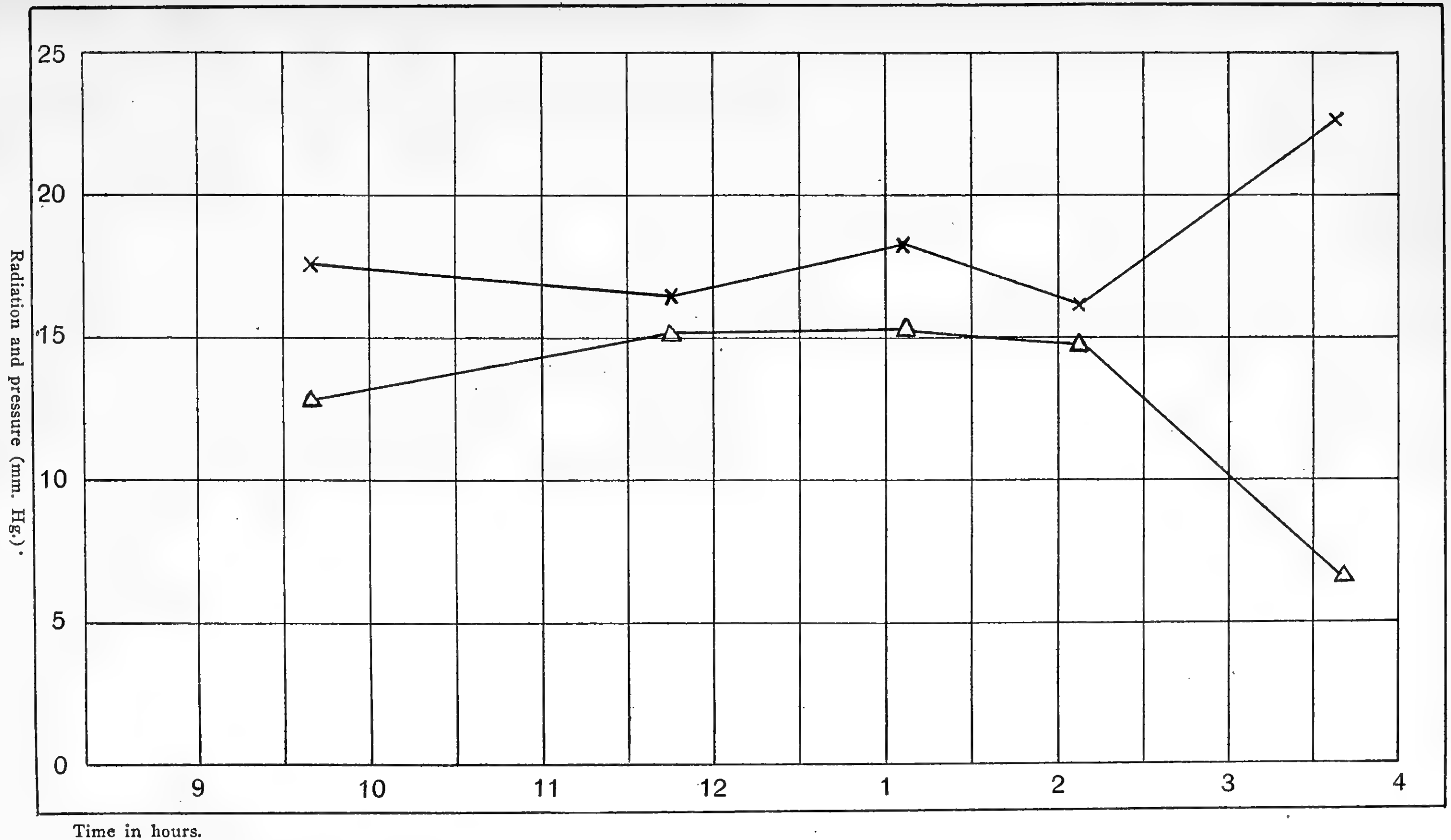

FIG. 24.—Nocturnal radiation x and water-vapor pressure Δ. Mt. Whitney, Cal. (altitude 4,420 m.), August 2, 1913.

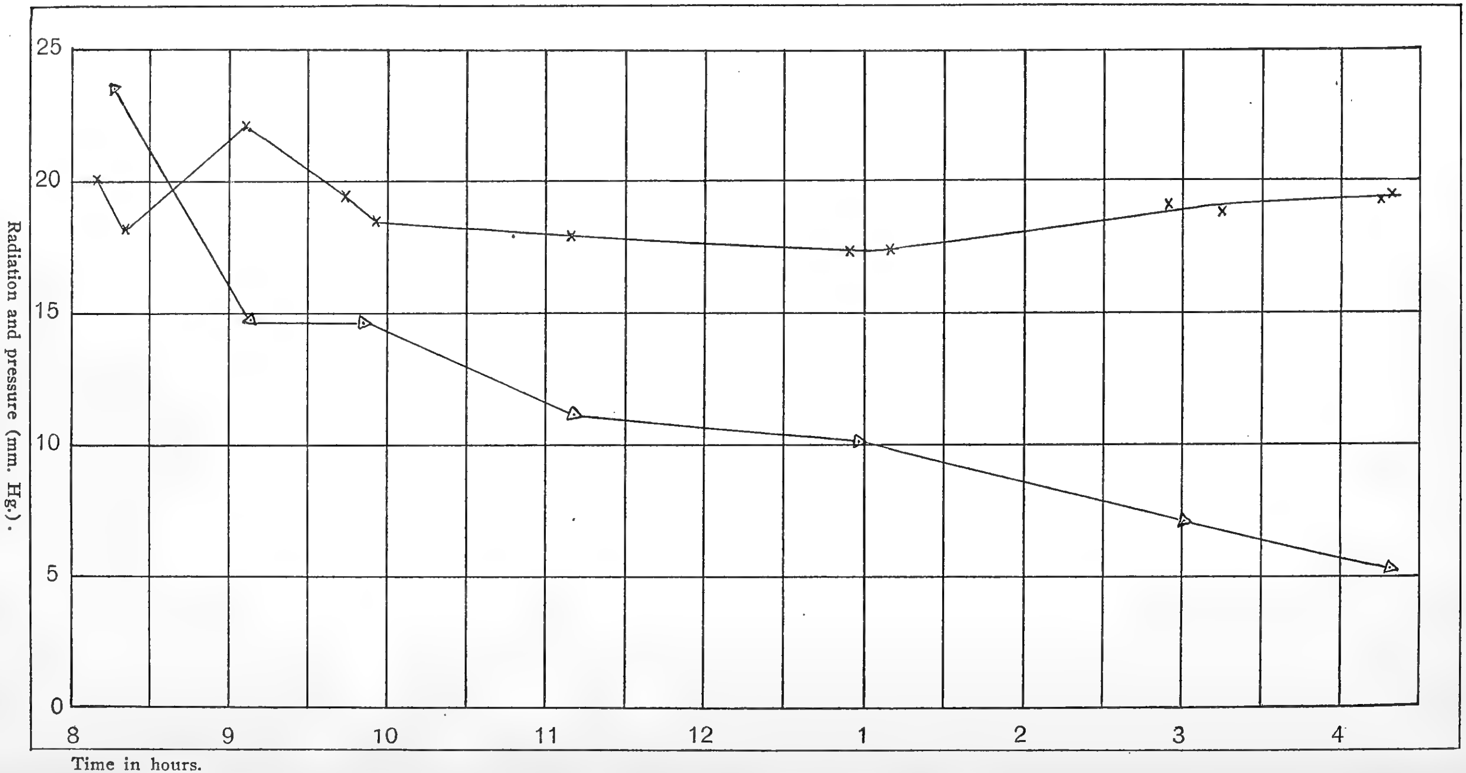

FIG. 25.—Nocturnal radiation x and water-vapor pressure Δ. Mt. Whitney, Cal. (altitude 4,420 m.), August 11, 1913.

EXPLANATION OF TABLES XIV TO XXI

In the following tables are included all the observations at Indio (Table XIV), at Lone Pine (Table XV), at Lone Pine Canyon (Table XVI), at Mount San Antonio (Table XVII), at Mount San Gorgonio (Table XVIII), at Mount Whitney (Table XIX), and at Mount Wilson (Table XX). Upon the values given in these tables, the studies of the total radiation are based. In the tables are given: (1) the date, (2) the time, (3) the temperature (t), (4) the pressure of aqueous vapor (H), (5) the radiation of a black body (S_t) at the temperature (t) (Kurlbaum's constant), (6) the observed effective radiation (R_t), (7) the difference between S_t and R_t, here defined as being the radiation of the atmosphere, (8) this radiation reduced to a temperature of 20° C., in accordance with the discussion presented in chapter V: B ($E_{a20°}$), and finally *Remarks* in regard to the general meteorological conditions prevailing at the time of observation. With each night of observation is given the initials of the observers: A. K. Ångström, E. H. Kennard, F. P. Brackett, R. D. Williams, and W. Brewster.

TABLE XIV

Place: Indio. Altitude: 0 m. B = 760 mm. Instrument No. 17

Date	Time	t	H	S_t	R_t	S_t-R_t	E_{a20}	Remarks
July 22	7:50	26.6	13.59	0.618	0.123	0.495	0.453	A. K. Å. Cloudless sky, wind W., calm.
	8:40	24.9	13.67	0.604	0.118	0.486	0.455	
	10:00	28.3	12.24	0.632	0.129	0.503	0.451	
	10:15	27.5	11.86	0.625	0.143	0.482	0.436	
	11:00	27.8	11.43	0.628	0.147	0.481	0.433	
	12:10	26.1	10.87	......	......	......	......	
	1:00	26.4	11.13	0.616	0.140	0.476	0.438	
	2:15	25.8	10.64	0.611	0.140	0.471	0.436	
	3:45	23.6	10.77	0.593	0.133	0.460	0.440	
	4:30	22.8	10.67	0.587	0.136	0.451	0.435	
July 23	7:50	29.5	11.33	0.642	0.193	0.449	0.396	A. K. Å. Sky perfectly cloudless calm.
	9:00	28.1	11.30	0.630	0.193	0.437	0.391	
	10:15	25.2	11.56	0.606	0.182	0.424	0.394	
	11:05	24.7	11.41	0.602	0.181	0.421	0.396	
	12:45	23.6	10.47	0.593	0.172	0.421	0.402	
	2:15	23.3	10.52	0.591	0.178	0.413	0.397	
	3:30	22.2	10.52	0.582	0.175	0.407	0.395	
	4:25	21.0	10.82	0.572	0.171	0.401	0.396	
July 24	7:45	29.5	9.65	0.642	0.183	0.459	0.404	W B. Sky perfectly cloudless, calm.
	9:00	27.5	9.30	0.625	0.183	0.442	0.399	
	10:05	25.0	10.97	0.605	0.166	0.439	0.410	
	11:15	23.9	10.69	0.596	0.169	0.427	0.405	
	12:10	23.0	10.31	0.588	0.169	0.419	0.402	
	1:05	23.0	9.37	0.588	0.173	0.415	0.398	
	2:00	21.2	9.65	0.573	0.170	0.403	0.397	
	3:10	21.2	8.81	0.573	0.174	0.399	0.393	
	4:05	20.6	8.43	0.568	0.172	0.396	0.393	
	4:20	19.5	8.15	0.560	0.163	0.397	0.400	

TABLE XV

Place: Lone Pine. Altitude: 1,140 m. B = 650 mm. Instrument No. 18

Aug. 2	9:25	18.1	10.11	0.548	0.145	0.403	0.415	F. P. B., R. D. W. Cloudless, calm.
	10:00	19.4	8.99	0.559	0.144	0.415	0.419	
	11:05	17.4	9.71	0.543	0.127	0.416	0.433	
	12:10	21.3	10.20	0.575	0.149	0.426	0.420	
	1:05	18.2	10.58	0.548	0.134	0.414	0.426	
	2:00	18.1	10.50	0.547	0.136	0.411	0.423	
	3:30	17.5	10.24	0.544	0.141	0.403	0.419	
	4.00	16.7	10.01	0.538	0.151	0.387	0.407	
Aug. 3	8:00	20.0	8.44	0.564	0.175	0.389	0.389	R. D. W., F. P. B. Cloudless, calm.
	9:00	22.5	7.47	0.584	0.172	0.412	0.399	
	10:00	21.1	8.00	0.572	0.182	0.390	0.384	
	11:00	18.8	8.28	0.554	0.173	0.381	0.389	
	12:00	17.8	7.07	0.546	0.174	0.372	0.385	
	1:00	15.2	8.54	0.527	0.139	0.388	0.415	
	2:25	16.8	7.73	0.538	0.169	0.369	0.386	
	3:00	13.0	8.47	0.512	0.168	0.344	0.379	
	4:00	13.4	8.29	0.514	0.147	0.367	0.402	

TABLE XV—Continued

Place: Lone Pine. Altitude: 1,140 m. B = 650 mm. Instrument No. 18

Date	Time	t	H	S_t	R_t	$S_t - R_t$	E_{a20}	Remarks
Aug. 4	10:07	19.9	8.43	0.563	0.169	0.394	0.395	F. P. B. Cloudless, calm.
	11:00	19.0	7.08	0.556	0.167	0.389	0.395	
	12:00	17.3	9.01	0.542	0.183	0.359	0.374	R. D. W. Radiation variable.
	1:00	13.2	8.39	0.513	0.170	0.343	0.376	
	2:05	12.7	7.59	0.509	0.167	0.342	0.378	
	3:05	15.0	6.99	0.525	0.154	0.371	0.397	
	4:05	13.3	6.90	0.514	0.189	0.325	0.356	
Aug. 5	8:15	24.6	5.87	0.602	0.212	0.390	0.366	R. D. W., F. P. B. Radiation fluctuating.
	9:05	23.0	5.79	0.588	0.215	0.373	0.358	
	10:00	17.1	7.38	0.541	0.195	0.346	0.360	
	11:00	21.4	5.46	0.575	0.205	0.370	0.363	
	12:00	15.6	6.33	0.530	0.191	0.339	0.359	
	1:05	12.4	6.96	0.507	0.166	0.341	0.378	
	2:05	14.8	5.97	0.524	0.189	0.335	0.360	
	3:05	14.4	6.52	0.521	0.174	0.347	0.375	
	4:05	14.4	5.96	0.521	0.170	0.351	0.379	
Aug. 9	8:00	21.1	7.99	0.572	0.180	0.392	0.387	R. D. W., F. P. B. Hazy in the evening, perfectly cloudless.
	9:00	22.4	7.18	0.583	0.177	0.406	0.394	
	10:00	18.8	8.29	0.554	0.168	0.386	0.394	
	11:00	16.9	7.61	0.540	0.163	0.377	0.394	
	12:00	14.6	8.03	0.523	0.143	0.380	0.408	
	1:00	12.7	8.13	0.509	0.142	0.367	0.406	
	2:00	12.2	8.11	0.506	0.139	0.367	0.407	
	3:05	10.7	5.42	0.496	0.139	0.357	0.405	
	4:00	10.6	8.39	0.495	0.133	0.362	0.411	
Aug. 10	8:20	21.9	7.12	0.579	0.196	0.383	0.374	E. H. K. Few scattered clouds at N. horizon in the evening. Perfectly cloudless after 9:00.
	9:00	22.0	7.25	0.580	0.211	0.369	0.360	
	9:10	......	......	......	0.202	0.378	0.368	
	10:10	21.1	7.38	0.572	0.194	0.378	0.373	
	10:20	......	......	......	0.197	0.375	0.370	
	11:00	20.9	7.48	0.571	0.209	0.362	0.359	
	11:10	......	......	......	0.199	0.372	0.369	
	12:05	19.8	7.61	0.562	0.195	0.367	0.371	
	12:15	......	......	......	0.201	0.361	0.365	
	1:00	16.9	8.05	0.540	0.170	0.370	0.387	
	3:05	16.4	8.23	0.536	0.159	0.377	0.389	
	3:15	16.4	8.23	0.536	0.162	0.374	0.393	
	4:30	12.7	8.01	0.510	0.154	0.356	0.393	
	4:40	......	......	0.510	0.147	0.363	0.400	
Aug. 11	8:25	20.5	6.40	0.568	0.189	0.379	0.377	E. H. K. Perfectly cloudless. Breezy.
	9:00	24.6	6.12	0.602	0.197	0.405	0.381	
	9:10			0.602	0.223	0.379	0.356	
	10:00	23.2	5.78	0.590	0.204	0.386	0.371	
	10:10			0.590	0.204	0.386	0.371	
	11:00	20.7	5.78	0.569	0.202	0.367	0.363	
	11:10			0.569	0.207	0.362	0.358	
	12:00	18.9	6.59	0.555	0.204	0.351	0.358	
	12:10			0.555	0.210	0.345	0.352	
	1:00	14.3	6.18	0.521	0.189	0.332	0.359	
	1:10			0.521	0.176	0.345	0.372	
	2:00	12.0	5.78	0.505	0.190	0.315	0.351	
	2:10			0.505	0.176	0.329	0.365	

Table XV—Continued

Place: Lone Pine. Altitude: 1,140 m. B = 650 mm. Instrument No. 18

Date	Time	t	H	S_t	R_t	$S_t - R_t$	E_{a20}	Remarks
Aug. 11	3:00	11.6	6.27	0.502	0.196	0.306	0.343	E. H. K. Perfectly cloudless, fluctuations.
	3:25			0.502	0.155	0.347	0.384	
	4:10	9.8	5.36	0.490	0.187	0.303	0.349	
	4:20			0.490	0.180	0.310	0.356	
	4:40	10.0	5.16	0.491	0.173	0.318	0.364	
	4:50			0.491	0.156	0.335	0.385	
	5:00	8.9	5.37	0.484	0.171	0.313	0.365	
Aug. 12	7:00	25.6	7.31	0.610	0.208	0.402	0.372	E. H. K. Perfectly cloudless, windy.
	7:20	......	......	0.610	0.212	0.398	0.369	
	7:25	25.2	5.56	0.606	0.209	0.397	0.369	
	7:45	......	......	0.606	0.211	0.395	0.367	
	8:00	26.0	4.71	0.613	0.199	0.414	0.381	
	8:10			0.613	0.220	0.393	0.362	
	8:35	......	......	0.613	0.218	0.395	0.369	
	9:00	23.9	4.49	0.596	0.209	0.387	0.368	
	9:10			0.596	0.220	0.376	0.357	
	10:00	20.6	5.30	0.568	0.195	0.373	0.371	
	10:10			0.568	0.197	0.371	0.369	
	11:15	18.7	5.08	0.553	0.197	0.356	0.363	
	11:25			0.553	0.208	0.345	0.352	
	12:00	20.5	3.85	0.568	0.189	0.379	0.377	
	12:10			0.568	0.220	0.348	0.346	
	1:00	20.5	3.67	0.568	0.192	0.376	0.374	
	1:10			0.568	0.184	0.384	0.382	
	2:05	15.7	5.26	0.530	0.172	0.358	0.380	
	2:20			0.530	0.163	0.367	0.389	
	3:05	15.6	5.91	0.529	0.169	0.360	0.382	
	3:15			0.529	0.154	0.375	0.397	
Aug. 14	8:20	23.4	7.52	0.592	0.241	0.351	0.337	A. K. Å. Very clear
	8:25	......	......	0.592	0.231	0.361	0.347	
	8:50	21.3	4.69	0.574	0.231	0.343	0.338	

Table XVI

Place: Lone Pine Canyon. Altitude: 2,500 m. B = 498 mm. Instrument No. 22

Date	Time	t	H	S_t	R_t	$S_t - R_t$	E_{a20}	Remarks
Aug. 4	8:05	18.9	4.71	0.555	0.203	0.352	0.359	W. B. Cloudless.
	4:10	15.0	5.27	0.526	0.203	0.323	0.346	
Aug. 5	8:05	18.9	5.32	0.555	0.211	0.344	0.351	W. B. Cloudless.
	9:00	18.9	2.54	0.555	0.199	0.356	0.363	
	10:05	18.6	2.65	0.553	0.226	0.327	0.334	
	11:00	18.6	3.24	0.553	0.220	0.333	0.340	
	12:00	16.1	4.00	0.533	0.218	0.315	0.333	
	1:00	16.1	3.75	0.533	0.217	0.316	0.334	
	2:10	16.7	4.07	0.538	0.209	0.329	0.345	
	2:55	16.8	3.53	0.539	0.194	0.345	0.361	
	3:55	15.0	4.23	0.526	0.214	0.312	0.334	
Aug. 8	9:35	15.5	7.63	0.529	0.176	0.353	0.376	W. B. Cloudless.
	10:00	14.7	6.30	0.523	0.177	0.346	0.372	
Aug. 9	8:15	12.8	7.34	0.510	0.184	0.326	0.359	W. B. Cloudless.
	9:10	12.2	5.98	0.506	0.161	0.345	0.383	
	10:00	12.2	5.98	0.506	0.158	0.348	0.386	

TABLE XVI—Continued

Place: Lone Pine Canyon. Altitude: 2,500 m. B = 498 mm. Instrument No. 22

Date	Time	t	H	S_t	R_t	$S_t - R_t$	E_{a20}	Remarks
Aug. 9	10:55	12.5	6.09	0.508	0.154	0.354	0.391	W. B. Hazy but cloudless.
	12:00	12.8	5.52	0.510	0.169	0.341	0.375	
	1:00	11.9	5.88	0.504	0.169	0.335	0.374	
	2:00	12.8	5.18	0.508	0.161	0.347	0.382	
	3:00	12.0	5.04	0.505	0.169	0.336	0.375	
	3:55	12.0	5.04	0.505	0.147	0.358	0.397	
Aug. 10	9:15	12.2	5.93	0.506	0.166	0.340	0.378	W. B. Breezy, cloudless.
	3:10	10.6	6.53	0.495	0.172	0.323	0.367	
	4:00	10.6	6.06	0.495	0.168	0.327	0.371	

TABLE XVII

Place: Mt. San Antonio. Altitude: 3,000 m. B = 532 mm. Instrument No. 22

Date	Time	t	H	S_t	R_t	$S_t - R_t$	E_{a20}	Remarks
July 12	8:00	18.3	3.91	0.550	0.202	0.348	0.357	A. K. Å. Perfectly cloudless, windy.
	8:05	......	......	0.550	0.209	0.341	0.350	
	9:05	17.9	3.63	0.547	0.209	0.338	0.348	
	10:05	......	......	0.547	0.202	0.345	0.355	
	11:00	17.5	3.23	0.544	0.200	0.344	0.357	
	12:00	16.9	6.35	0.539	0.193	0.346	0.362	
	12:05	......	......	0.539	0.203	0.336	0.352	
	1:00	16.7	7.85	0.538	0.199	0.339	0.356	
	1:10	......	......	0.538	0.189	0.349	0.366	
	2:00	16.6	9.55	0.537	0.188	0.349	0.366	
	2:10	......	......	0.537	0.187	0.350	0.367	
	3:00	16.4	6.48	0.536	0.195	0.341	0.358	
	3:10	16.2	8.10	0.534	0.131	0.403	......	Clouds after 3:00.
	4:05	......	......	0.534	0.164	0.370	......	
July 13	7:10	11.8	2.46	0.503	0.203	0.300	0.335	A. K. Å. Hazy at N. horizon, cloudless.
	7:30	11.2	2.60	0.499	0.191	0.308	0.346	
	8:30	10.7	2.22	0.496	0.213	0.283	0.321	
	8:50	10.8	2.36	0.496	0.220	0.276	0.312	
	9:45	11.2	1.99	0.499	0.211	0.288	0.324	
	10:50	10.0	2.27	0.491	0.219	0.272	0.313	
	12:30	11.3	1.63	0.500	0.225	0.275	0.309	
	2:15	9.7	2.16	0.489	0.220	0.269	0.310	
	4:15	10.0	2.27	0.491	0.221	0.270	0.310	

TABLE XVIII

Place: Mt. San Gorgonio. Altitude: 3,500 m. B = 495 mm. Instrument No. 22

Date	Time	t	H	S_t	R_t	$S_t - R_t$	E_{a20}	Remarks
July 23	8:00	2.0	2.95	0.438	0.204	0.234	0.300	E. H. K. After stormy and rainy day perfectly cloudless night.
	9:00	1.1	2.66	0.432	0.215	0.217	0.282	
	10:20	1.3	......	0.433	0.215	0.218	0.283	
	11:00	0.9	......	0.431	0.205	0.226	0.294	
	12:05	0.9	......	0.431	0.207	0 224	0.292	
	1:20	0.4	......	0.428	0.208	0.220	0.290	
	2:00	0.2	2.61	0.426	0.208	0.218	0.288	
	3:00	0.0	1.80	0.425	0.208	0.217	0.288	
	4:00	—0.6	2.21	0.421	0.198	0.223	0.299	
July 24	8:20	2.8	1.91	0.443	0.211	0.232	0.295	F. P. B. Perfectly cloudless.
	9:00	2.3	1.54	0.440	0.215	0.225	0.289	
	10:00	2.2	......	0.439	0.215	0.224	0.287	
	11:00	1.6	1.88	0.435	0.223	0.212	0.274	
	12:00	1.8	1.14	0.436	0.221	0.215	0.276	

TABLE XIX

Place: Mt. Whitney. Altitude: 4,420 m. B = 446 mm. Instrument No. 17

Date	Time	t	H	S_t	R_t	S_t-R_t	E_{a20}	Remarks
Aug. 1	11:00	—2.9	3.70	0.407	0.189	0.218	0.302	E. H. K. Cloudless only about 11:00.
Aug. 2	9:40	—0.8	3.23	0.420	0.176	0.244	0.327	A. K. Å. Cloudless after cloudy and windy evening.
	11:45	—1.4	3.81	0.416	0.165	0.251	0.345	
	1:05	—1.4	3.79	0.416	0.183	0.233	0.320	
	2:05	—1.9	3.61	0.413	0.160	0.253	0.343	
	3:35	—1.1	1.68	0.418	0.226	0.192	0.260	
Aug. 3	7:30	0	3.75	0.425	0.194	0.231	0.306	E. H. K. Perfectly cloudless, balloon sent up, calm.
	8:05	0.3	3.30	0.413	0.207	0.206	0.271	
	9:05	—0.1	3.80	0.424	0.217	0.207	0.277	
	10:10	......	......	0.424	0.170	0.254	0.338	
	11:00	—0.1	3.18	0.424	0.177	0.247	0.329	
	12:05	—0.4	3.15	0.422	0.160	0.262	0.350	
	1:00	—0.6	2.97	0.421	0.171	0.250	0.335	
	2:10	—1.1	2.90	0.418	0.163	0.255	0.344	
	3:25	—1.1	1.70	0.418	0.167	0.251	0.339	
	4:10	—1.3	1.40	0.417	0.183	0.234	0.316	
	4:25	......	......	0.417	0.179	0.238	0.321	
	4:35	—1.6	1.76	0.415	0.182	0.233	0.317	
	4:45	......	......	0.415	0.190	0.225	0.306	
	5:00	—1.7	1.73	0.414	0.183	0.231	0.314	
Aug. 4	8:05	1.4	3.28	0.434	0.195	0.239	0.310	A. K. Å. Perfectly cloudless, balloon up, calm.
	8:25	......	......	0.434	0.199	0.235	0.304	
	9:00	1.3	2.59	0.433	0.193	0.240	0.311	
	9:10	......	......	0.433	0.195	0.238	0.308	
	10:00	1.1	2.39	0.432	0.190	0.242	0.315	
	10:10	......	......	0.432	0.194	0.238	0.309	
	11:00	0.6	2.46	0.429	0.194	0.235	0.308	
	11:10	......	......	0.429	0.189	0.240	0.314	
	12:00	0.6	2.42	0.429	0.188	0.241	0.315	
	12:10	......	......	0.429	0.188	0.241	0.315	
	1:00	0.6	2.44	0.429	0.180	0.249	0.327	
	1:10	......	......	0.429	0.182	0.247	0.324	
	2:15	0.0	2.32	0.425	0.179	0.246	0.326	
	2:30	......	......	0.425	0.184	0.241	0.319	
	3:00	0.2	2.00	0.426	0.213	0.213	0.281	
	3:10	......	......	0.426	0.228	0.198	0.262	
	3:20	0.0	1.93	0.425	0.200	0.225	0.298	
	3:30	......	......	0.425	0.210	0.215	0.285	
	4:00	0.0	2.21	0.425	0.202	0.223	0.295	
	4:10	......	......	0.425	0.223	0.202	0.267	
Aug. 5	7:10	1.9	2.67	0.437	0.179	0.258	0.332	E. H. K. Balloon up, breezy after 10:00.
	7:40	......	......	0.437	0.190	0.247	0.317	
	8:05	1.8	2.87	0.436	0.182	0.254	0.326	
	8:10	......	......	0.436	0.189	0.247	0.317	
	9:00	1.3	2.74	0.433	0.191	0.242	0.313	
	9:10	......	......	0.433	0.200	0.233	0.302	
	10:00	1.1	2.06	0.432	0.188	0.244	0.317	
	10:45	......	......	0.432	0.175	0.257	0.334	
	11:00	1.1	1.83	0.432	0.195	0.237	0.308	
	11:10	......	......	0.432	0.199	0.233	0.303	
	12:00	0.6	1.90	0.429	0.197	0.232	0.304	
	12:10	......	......	0.429	0.198	0.231	0.303	

TABLE XIX—Continued

Place: Mt. Whitney. Altitude: 4,420 m. B = 442 mm. Instrument No. 17

Date	Time	t	H	S_t	R_t	$S_t - R_t$	E_{a20}	Remarks
Aug. 5	1:10	0.3	1.86	0.427	0.185	0.242	0.318	E. H. K. Perfectly cloudless
	1:20	......	......	0.427	0.192	0.235	0.309	
	2:10	0.6	1.81	0.429	0.191	0.238	0.312	
	2:20	......	......	0.429	0.198	0.231	0.302	
	3:00	0.3	1.32	0.427	0.181	0.246	0.323	
	3:05	......	......	0.427	0.187	0.240	0.316	
	4:05	0.6	1.52	0.429	0.173	0.256	0.335	
	4:20	......	......	0.429	0.176	0.253	0.332	
Aug. 8	9:45	—1.3	3.59	0.417	0.173	0.244	0.330	A. K. Å. Cloudless after 9:30.
	10:00	......	......	0.417	0.162	0.255	0.344	
	10:35	—1.4	3.35	0.416	0.167	0.249	0.337	
	10.55	......	......	0.416	0.161	0.255	0.345	
Aug. 9	12:30	—3.0	3.51	0.407	0.150	0.257	0.356	A. K. Å. Cloudless after foggy afternoon.
	12:45	......	......	0.407	0.154	0.253	0.351	
	2:30	—3.6	3.07	0.403	0.152	0.251	0.351	
	4:35	—3.7	2.46	0.402	0.160	0.242	0.338	
	4:45	......	......	0.402	0.161	0.241	0.337	
Aug. 11	8:10	—2.2	2.37	0.412	0.201	0.211	0.289	A. K. Å. Cloudless after clear day. Radiation variable.
	8:20	......	......	0.412	0.181	0.231	0.316	
	9:05	—2.3	1.47	0.411	0.221	0.190	0.260	
	9:45	—2.4	1.47	0.410	0.196	0.214	0.293	
	9:55	......	......	0.410	0.183	0.227	0.311	
	11:10	—2.7	1.12	0.409	0.179	0.230	0.316	
	12:55	—3.0	1.02	0.407	0.172	0.235	0.325	
	1:10	......	......	0.407	0.174	0.233	0.322	
	2:55	—2.6	0.69	0.409	0.191	0.218	0.300	
	3:15	......	......	0.409	0.189	0.220	0.303	
	4:15	—2.5	0.54	0.410	0.193	0.217	0.298	
	4:20	......	......	0.410	0.194	0.216	0.297	
Aug. 12	8:00	—1.4	1.17	0.416	0.194	0.222	0.300	A. K. Å. Clouds after 8:30.
	8:10	......	......	0.416	0.192	0.224	0.303	

TABLE XX

Place: Mt. Wilson. Altitude: 1,730 m. B = 615 mm. Instrument No. 17

Date	Time	t	H	S_t	R_t	$S_t - R_t$	E_{a20}	Remarks
Aug. 27	9.10	18.9	12.37	0.555	0.143	0.412	0.420	A. K. Å. Calm and perfectly cloudless night.
	9:25	......	......	0.555	0.140	0.415	0.423	
	10:00	18.8	11.45	0.554	0.147	0.407	0.415	
	10:20	18.5	11.34	0.552	0.152	0.400	0.410	
	11:00	18.3	10.92	0.550	0.150	0.400	0.411	
	11:10	......	......	0.550	0.151	0.399	0.410	
	12:00	18.2	10.97	0.549	0.149	0.400	0.412	
	12:10	......	......	0.549	0.151	0.398	0.410	
	12:55	18.4	11.13	0.551	0.145	0.406	0.416	
	1:05	......	......	0.551	0.146	0.405	0.415	
	2:00	17.8	11.17	0.546	0.141	0.405	0.419	
	2:10	......	......	0.546	0.141	0.405	0.419	
	2:50	17.8	11.04	0.546	0.147	0.399	0.413	
	3:00	......	......	0.546	0.147	0.399	0.413	
	3:40	18.5	10.69	0.552	0.155	0.397	0.407	
	3:50	......	......	0.552	0.154	0.398	0.408	

TABLE XXI

Date	Time	Instr.	Place Observer	Altitude	Radiation	Humidity	Temp.	Remarks
Aug. 26	8:45	18	Bassour. C. G. A.	1160 m.	0.217	3.8	21.5°	Sky perfectly cloudless
26	9:00	17	Mousaïa Valley. A. K. Å.	540 m.	0.174	8.0	19.6°	Sky perfectly cloudless
27	9:05	18	Bassour. C. G. A.	1160 m.	0.188	8.5	21.5°	Sky perfectly cloudless
27	9:00	17	Peak of Mousaïa. A. K. Å.	1610 m.	0.183	8.6	18.2°	Sky perfectly cloudless
27	7 to 5	17	Peak of Mousaïa. A. K. Å.	1610 m.	0.186	7.7	16.8°	Sky perfectly cloudless

APPENDIX I

FREE-AIR DATA IN SOUTHERN CALIFORNIA, JULY AND AUGUST, 1913[1]

By the Aerial Section, U. S. Weather Bureau—Wm. R. Blair in Charge

[Dated, Mount Weather, Va., May 26, 1914]

The Astrophysical Observatory of the Smithsonian Institution, and the Mount Weather Observatory of the Weather Bureau co-operating during July and August, 1913, made observations in southern California: (*a*) Of solar radiation at high levels, by means of a photographically recording pyrheliometer, carried by free balloons; (*b*) of the total moisture content of the air above Mount Wilson, by means of the spectroscope; (*c*) of nocturnal radiation, by means of the K. Ångström compensation apparatus; (*d*) of the meteorological elements, air pressure, temperature, humidity, and movement, at different altitudes by means of meteorographs, carried by free balloons at Avalon, and by captive balloons at Lone Pine and at the summit of Mount Whitney. The pyrheliometric observations have already been discussed by C. G. Abbot in *Science,* March 6, 1914. It is the purpose of this present paper to communicate more particularly the meteorological observations.

A. The Free Balloon Observations

Morning and evening ascensions were made on July 23 and 24, 1913, and thereafter daily ascensions until August 12, 1913—23 ascensions in all. When a pyrheliometer was taken up, in addition to the meteorograph, the ascension for the day was so timed that the highest point would be reached about noon. On other days the ascensions were made shortly after sunrise or just before sunset. Table 1 shows the number of balloons recovered, their landing points, and other information of general interest.

Table 1.—*Statistics of sounding balloon flights from Avalon, Cal., during July and August, 1913*

Date	Hour	Balloons		Landing point	Horizontal distance traveled	Direction traveled	Highest altitude reached	Lowest temperature recorded
		Number	Ascensional force					
1913			*Kg.*		*Km.*		*M.*	*°C.*
July 23	6:06 a....	2	....	Huntington Beach, Cal....	42	NE.	25,160	−56.0
24	5:13 p....	2	0.8	Armada, Cal.	122	ENE.	20,389	−55.8
26	5:11 p....	2	0.8	San Diego, Cal.............	131	ESE.	....	....
27	4:57 p....	2	0.9	Oceanside, Cal............	91	E.	23,870	−64.7
28	5:05 p....	2	1.1	Chino, Cal..................	97	NE.	19,485	−62.6
29	11:10 a...	2	1.2	Los Angeles, Cal...........	80	N.	23,066	−60.4
30	10:54 a...	2	1.0	Atmore's Ranch, Cal.......	140	NNW.	32,643	−53.9
31	10:37 a...	2	1.6	Los Pasos Hills, Cal.......	122	NNW.	22,294	−58.9
Aug. 1	10:36 a...	2	1.4	New Hall, Cal.............	128	N.	23,466	−58.6
2	10:59 a...	2	1.3	Inglewood, Cal............	72	N.	21,302	−67.3
3	5:07 p....	2	0.9	Downey, Cal.	70	N.	17,428	−67.5
5	5:07 p....	2	0.8	Fullerton, Cal.............	75	NNE.	....	....
7	4:52 p....	2	0.8	Colton, Cal................	120	NE.	6,442	−25.2
8	5:23 p....	2	0.9	Baldwin Park, Cal.........	97	NNE.	14,100	−43.9
10	4:43 p....	2	0.9	Pacific Ocean.............	4	NW.	1,976	19.3

[1] Reprinted by permission from the Monthly Weather Review, July, 1914, pp. 410-426.

All free balloons were started at Avalon, Santa Catalina Island, Cal. Because of the possibility of the instrument coming down in the ocean, balloons were sent up in pairs and with a float. This float weighed approximately 450 grams. Each balloon was filled until it would lift decidedly everything to be sent up except the float The balloons were then attached to the system in such a way that when either of them burst it would detach itself from the system, which then sank to the earth's surface with the remaining balloon. This device by which the balloons are connected with

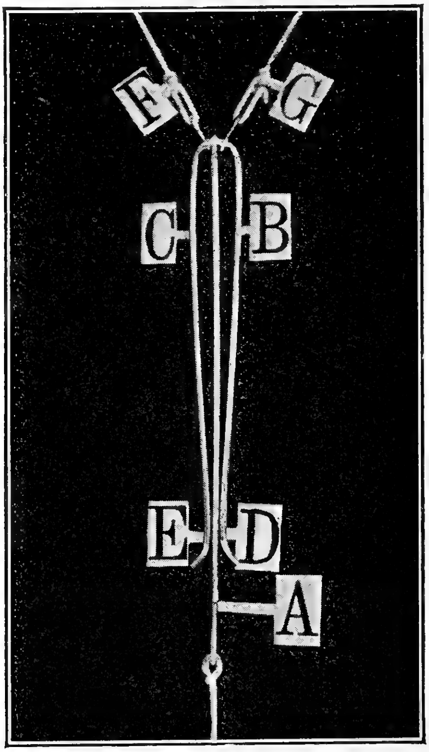

Fig. 1.—Device for releasing burst balloon.

the system and which serves the purpose of releasing the burst balloon is shown in figure 1. It is made of spring brass wire of approximately 2.4 mm. diameter. The pressure of the springs *B* and *C* on the wire *A* at the points *D* and *E* is sufficient to prevent the rings from slipping off in case cord *F* or *G* becomes slack. The weight of the burst balloon or of what is left of it slips the ring off easily. Cords *F* and *G* must be so short that they will not twist above the device.

The balloons used were of thick rubber, similar to those used at Huron in the early autumn of 1910 and at Fort Omaha in the late winter of 1911, but not so large. They were filled with electrolytic hydrogen which had been compressed in steel cylinders.

FIG. 2.—Record obtained in sounding balloon ascension of July 30, 1913.

TABLE 2.—*Temperatures recorded at different altitudes and ascensional rates of balloons for sounding balloon ascensions at Avalon, Cal., July and August, 1913.*

Altitude above surface	July 23		July 24		July 27		July 30		July 31		Aug. 1		Aug. 3		Means		Altitude above surface
	Rate of ascent	Tem-pera-ture	Rate of ascent	Tem-pera-ture	Rate of ascent	Tem-pera-ture	Rate of ascent	Tem-pera-ture	Rate of ascent	Tem-pera-ture	Rate of ascent	Tem-pera-ture	Rate of ascent	Tem-pera-ture	Rate of ascent	Tem-pera-ture	
Km.	*M. p. s.*	°*C.*	*M. p. s.*	°*C.*	*M. p. s.*	°*C.*	*M. p. s.*	°*C.*	*M. p. s.*	°*C.*	*M. p. s.*	°*C.*	*M. p. s.*	°*C.*	*M. p. s.*	°*C.*	*Km.*
1	4.02	18.5	3.14	14.6	3.33	13.3	1.58	18.2	3.97	21.6	2.78	24.2	2.90	30.0	3.10	20.1	1
2	4.17	12.6	3.33	14.7	3.27	9.6	1.55	20.3	4.17	18.7	2.90	18.3	3.03	21.8	3.20	16.6	2
3	4.44	5.5	3.51	8.1	3.27	2.5	1.63	18.5	4.27	12.8	3.03	10.9	3.06	14.6	3.32	10.4	3
4	4.63	− 1.0	3.58	2.4	3.27	− 4.7	1.81	11.0	4.33	5.8	3.17	3.6	3.09	7.3	3.41	3.5	4
5	4.76	− 7.9	3.51	− 2.8	3.33	−13.3	2.12	3.8	4.44	− 1.5	3.40	− 1.6	3.09	− 0.5	3.52	− 3.4	5
6	4.90	−14.7	3.51	− 9.3	3.44	−20.5	2.42	− 3.5	4.76	−11.3	3.51	− 9.5	3.21	− 8.2	3.68	−11.0	6
7	4.90	−21.6	3.51	−16.3	3.40	−29.0	2.67	− 9.8	5.21	−20.6	3.62	−17.5	3.27	−17.0	3.80	−18.8	7
8	4.90	−29.1	3.33	−20.8	3.40	−38.4	2.92	−15.9	5.46	−28.6	3.79	−23.5	3.27	−24.5	3.87	−25.8	8
9	4.83	−34.3	3.21	−26.3	3.40	−45.1	3.12	−22.8	5.65	−34.6	3.92	−30.0	3.12	−31.1	3.89	−32.0	9
10	4.90	−38.8	3.12	−31.7	3.33	−50.2	3.44	−30.2	5.95	−42.2	4.12	−36.6	3.14	−36.8	4.00	−38.1	10
11	5.56	−41.4	2.95	−38.2	3.30	−53.8	3.70	−37.3	6.41	−47.4	4.12	−43.2	3.33	−42.7	4.20	−43.4	11
12	5.13	−43.4	2.95	−42.4	3.37	−57.4	3.83	−44.2	6.41	−52.3	4.12	−49.4	3.33	−49.2	4.16	−48.3	12
13	5.56	−46.5	3.06	−45.5	3.37	−57.5	3.88	−49.1	6.54	−56.9	4.17	−52.3	3.37	−50.1	4.28	−51.1	13
14	4.07	−50.6	3.21	−46.6	3.44	−58.7	4.02	−51.3	6.67	−56.7	4.12	−49.8	3.37	−54.0	4.13	−52.5	14
15	4.17	−54.8	3.37	−49.6	3.88	−61.5	4.33	−49.2	6.67	−55.4	4.12	−50.5	3.37	−59.2	4.27	−54.3	15
16	4.63	−55.8	3.55	−52.2	4.57	−62.2	4.57	−50.3	6.80	−57.7	3.88	−54.0	3.33	−65.3	4.46	−56.8	16
17	5.38	−56.6	3.74	−55.4	3.70	−63.0	4.90	−49.8	6.94	−58.6	4.22	−56.0	3.51	−62.3	4.63	−57.4	17
18	6.29	−56.7	3.33	−55.6	3.47	−60.8	5.13	−53.0	7.58	−58.0	4.83	−58.0	3.51	−62.0	4.88	−57.7	18

The highest ascension of the series was made on July 30. This exceeds the previous highest ascension from this continent by more than two kilometers. The record obtained in this ascension is shown in figure 2.

In seven of the ascensions from which records were returned the instrument was carried to an altitude of 18 or more kilometers above sea level. The temperatures recorded and the ascensional rates of the balloons have been

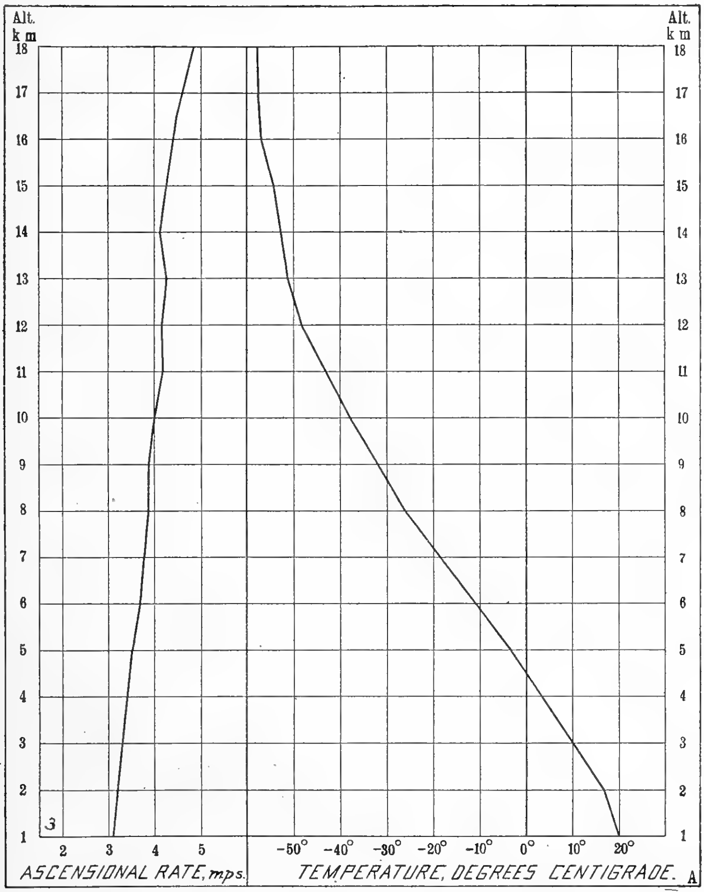

FIG. 3.—Relation between ascensional rates of balloons and air temperatures.

averaged and compared in table 2 and in figure 3. The mean of the observed temperatures in the seven ascensions does not show a minimum of temperature below the 18-kilometer level. The mean of the ascensional rates of the balloons shows, in general, an increase with altitude. Above the 18-kilometer level the individual ascensions show a decrease in the ascensional rates of the balloons soon after the minimum of temperature has been passed through. This relation between the air temperature and the ascensional rate of

the balloons is similar to that already found. (See Bulletin Mount Weather Observatory, Washington, 1911, 4 : 186.) It indicates that, in addition to the known factors entering into the ascensional rate of any balloon, there is the unknown factor of the difference in temperature between the gas in the balloon and the air through which the balloon is passing. While the temperature distribution in the free air is in general known, it would be impossible to predict, with sufficient accuracy for a particular ascension, the point of maximum ascensional rate or minor variations in the rate. On the other hand, careful observation of the ascensional rate of a free, sealed, rubber balloon might indicate fairly well the peculiarities of the temperature distribution at the time of the ascension. In this connection the author calls attention to an entirely erroneous statement in Bulletin of the Mount Weather Observatory, 4 :186, regarding the adiabatic cooling of hydrogen gas. The approximate rate of cooling per kilometer came in some way to be considered the rate to the 15-kilometer level. The statement based on this error should not have appeared, nor is it needed to account for the observed peculiarities in the ascensional rate of free rubber balloons under consideration.

The instruments used were the same as those used in previous series of soundings. The calibration of the instruments was similar to that for previous series, except that the pressure and temperature elements were calibrated in a smaller chamber in which ventilation and temperature were under somewhat better control and in which temperatures down to —60° C. could easily be obtained. (See Bulletin Mount Weather Observatory, Washington, 1911, 4 : 187.)

The data obtained in each ascension are presented in table 4 with interpolations at the 500-meter intervals up to 5 kilometers above sea level, and at 1-kilometer intervals above the 5-kilometer level. In figure 4 a diagram of the temperature-altitude relation is shown for each observation. Figure 5 shows the mean value of this relation for the period. The free air isotherms for the period are shown in figure 6. The horizontal projections of the balloon paths, as far as they could be observed, are shown in figure 7. Only one theodolite was used, the altitudes being computed from the observed air pressures.

An inversion of temperature, with the maximum temperature somewhere between the ½- and 2-kilometer levels, is shown in each curve of figure 4. This inversion of temperature is found, whether the observation be made in the morning, near noon, or in the late afternoon. It does not seem to accompany any particular wind direction. A similar inversion of temperature was observed in most of the ascensions made at Indianapolis, Fort Omaha, and Huron.

As shown in figure 5, the altitude at which the mean temperature for the period is a minimum is 17 kilometers. The minimum temperature observed in any ascension may be more than a kilometer above or below the height of this mean. In two ascensions, those of the 23d and 27th of July, the change of temperature with altitude begins to decrease at about the 8-kilometer level, while in the ascensions of August 2 and 3 this change does not take place until the 12-kilometer level. The temperature change from day to day is best shown in figure 6. The lowest temperature observed, —67.5° C., was at about the 16.5-kilometer level on August 3. About the same temperature had been observed at the 16-kilometer level on the day before.

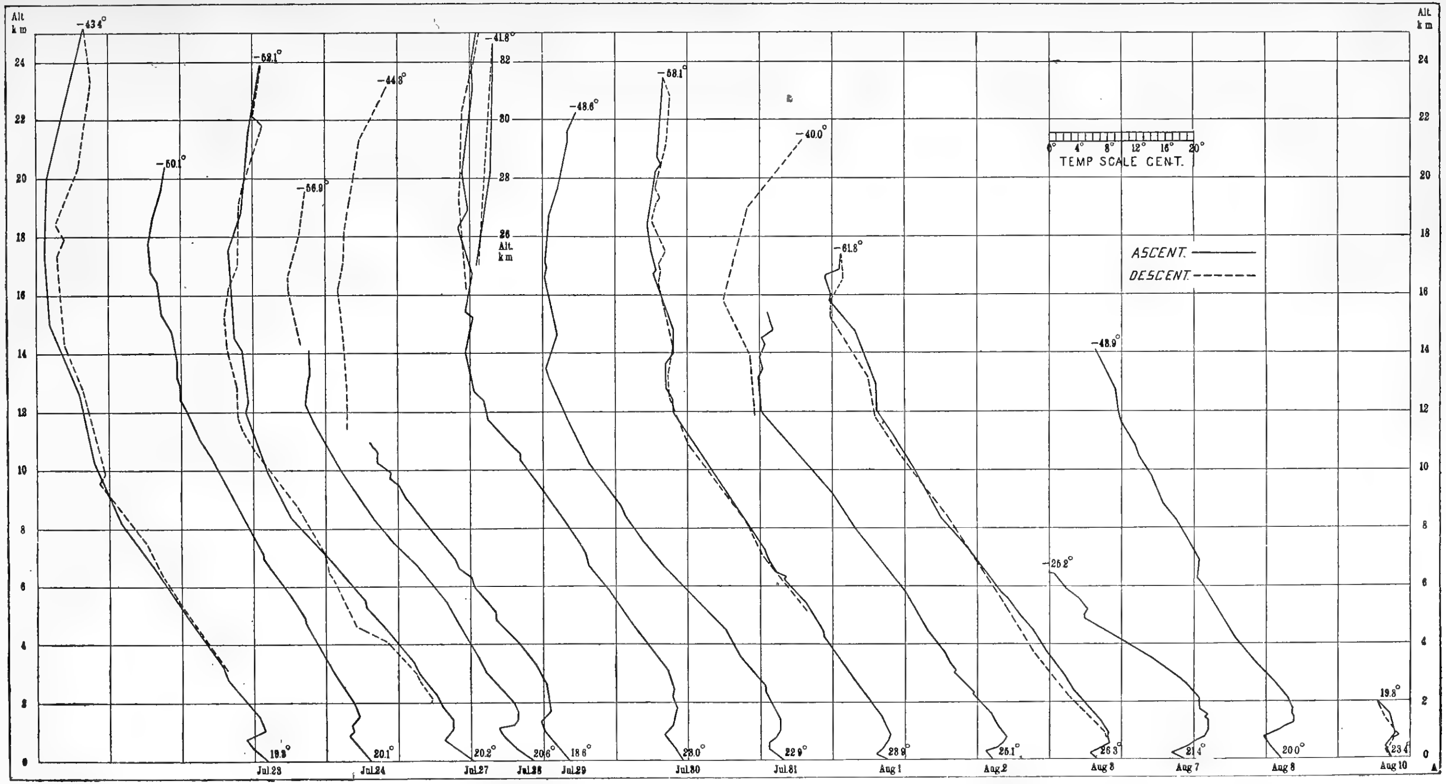

FIG. 4.—Vertical temperature gradients at Avalon, Cal., July 23-August 10, 1913.

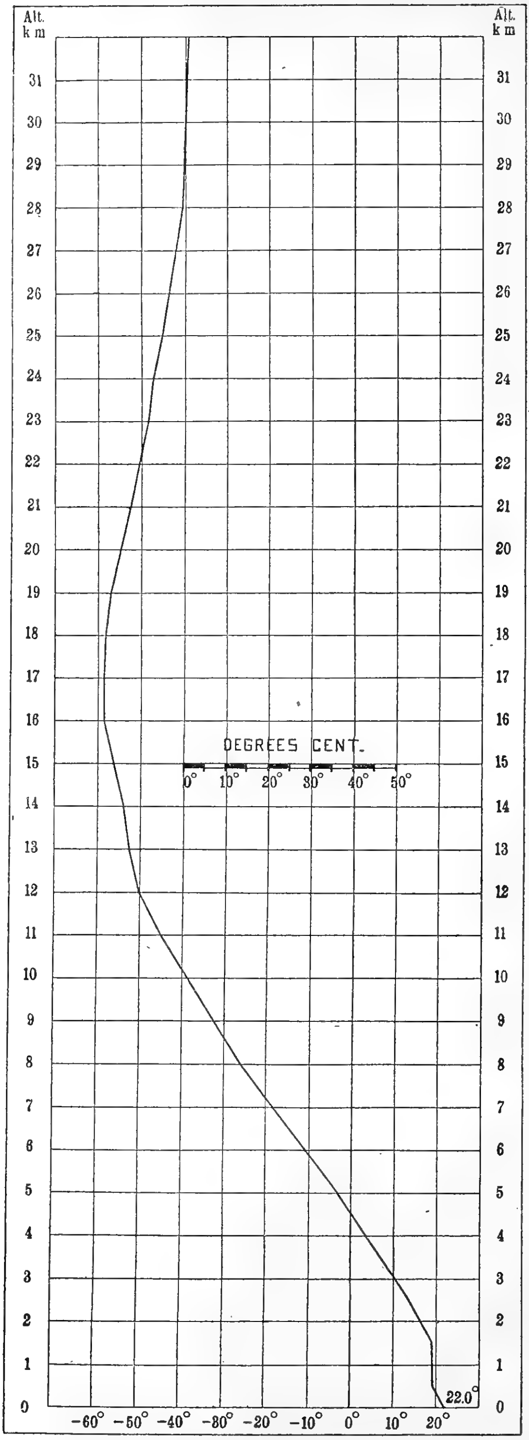

FIG. 5.—Curve showing mean temperature gradient at Avalon, Cal., July 23-August 3, 1913.

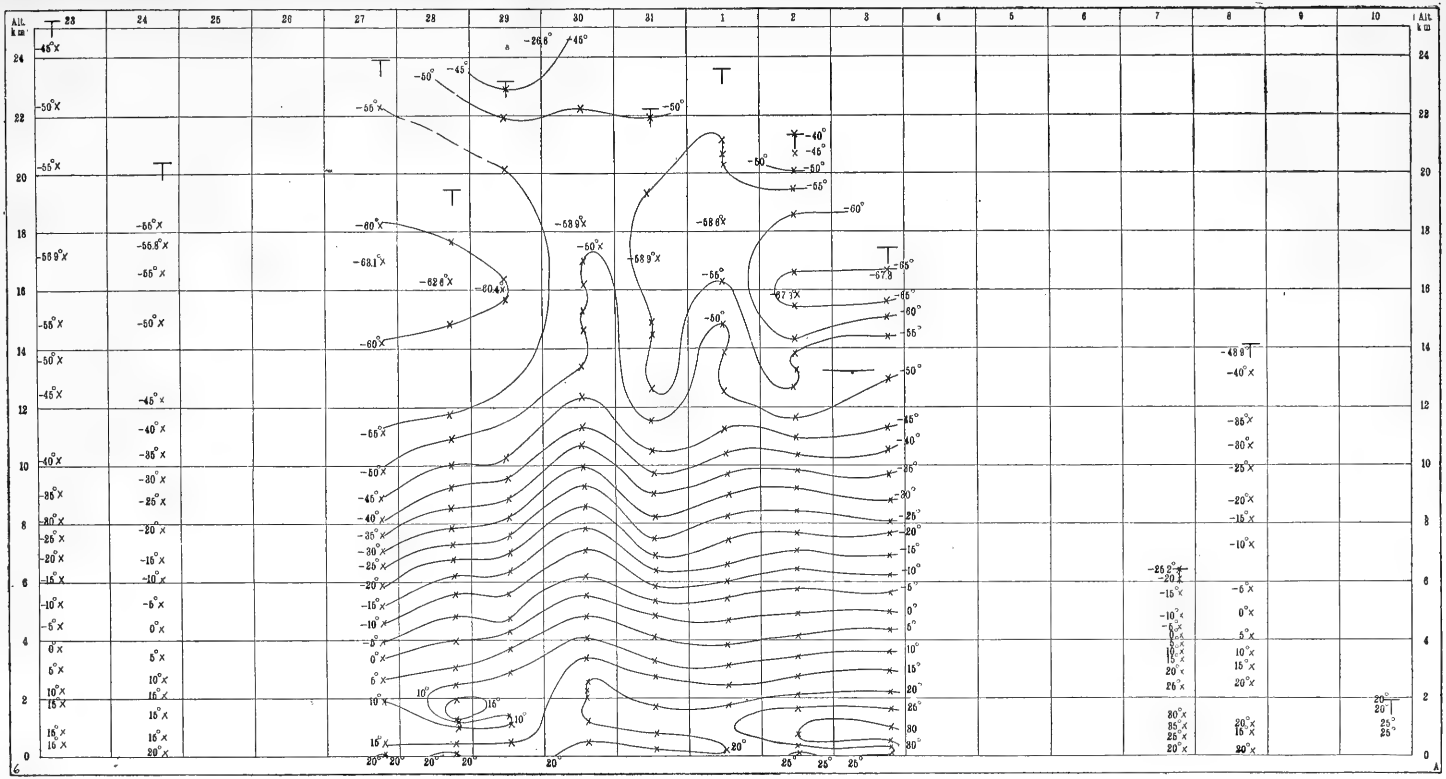

FIG. 6.—Free-air temperatures at Avalon, Cal., July 23-August 10, 1913.

FIG. 7.—Pressure distribution in the western United States, July 22-28, 1913.

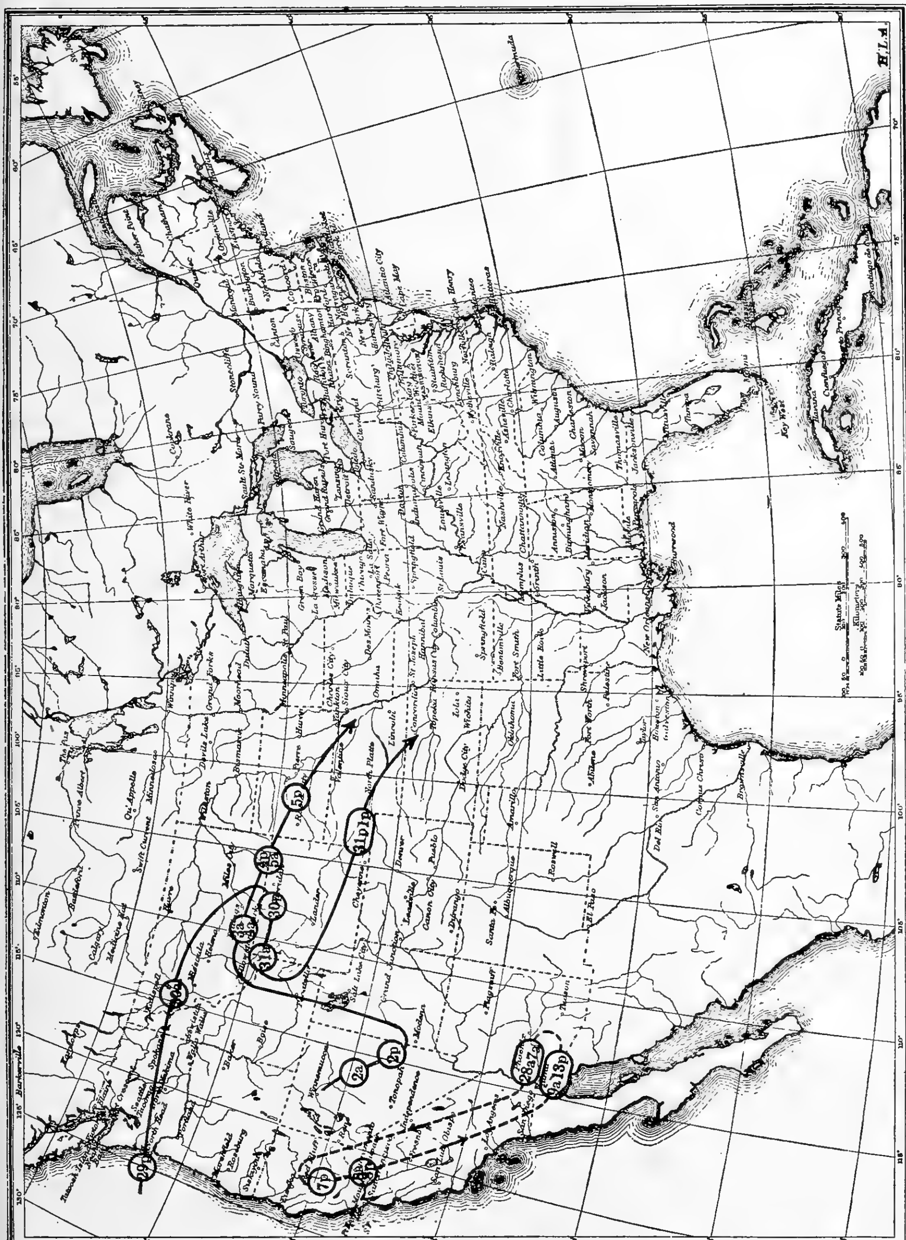

Fig. 8.—Pressure distribution in the western United States, July 29-August 13, 1913.

A comparison of the curve shown in figure 5 with that shown in the Bulletin of the Mount Weather Observatory, 4: 302, figure 31, shows the surface temperature indicated in figure 5 higher by 6.4° C., the minimum temperature lower by 3.5° C., the maximum next above this minimum less than 2° C. lower than the corresponding values shown in figure 31. The minimum temperature shown in figure 5 occurs at an altitude higher by 1.5 kilometers than that shown in figure 31. The maximum temperature next above the minimum

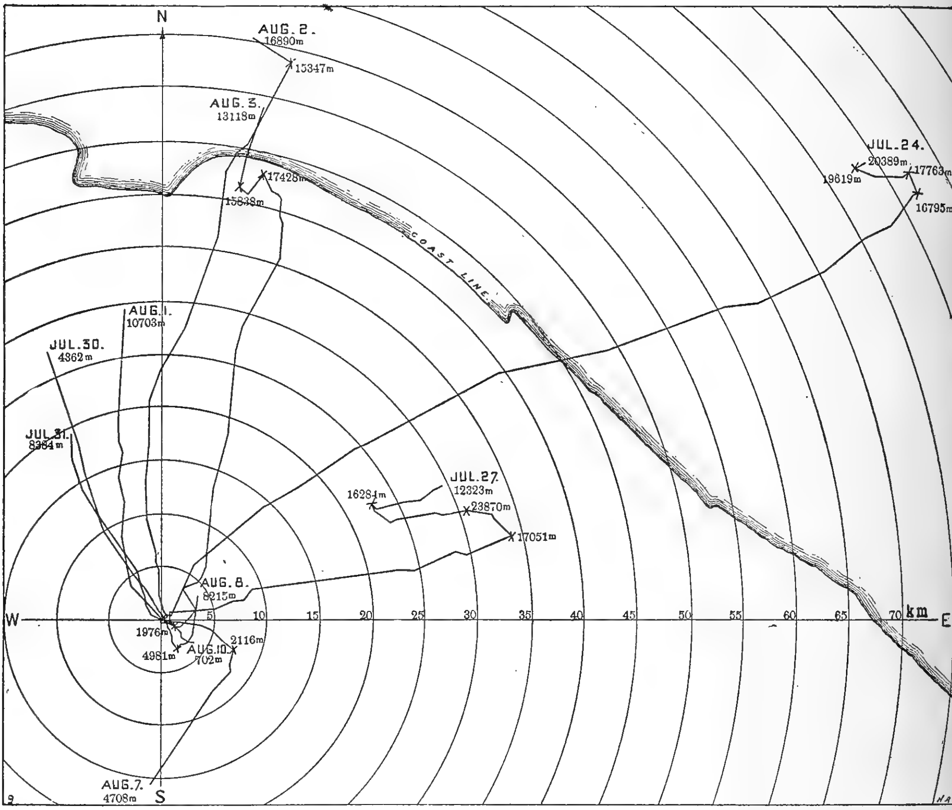

FIG. 9.—Horizontal projections of the paths of the sounding balloons liberated at Avalon, Cal., July 23-August 10, 1913.

temperature is shown at about the same altitude in both curves. The curves have the same general appearance. That shown in figure 5 represents summer conditions at latitude 33° N. That shown in figure 31 represents conditions in all seasons, to some extent, the late summer and early autumn being better represented than the other seasons, at about latitude 40° N.

The variations of humidity with altitude and from day to day are rather closely related to the variations of temperature. In table 3 the absolute humidities observed have been assembled and a mean shown.

TABLE 3.—*Absolute humidity (grams per cubic meter) at various levels on different dates, Avalon, Cal., 1913*

Date	Altitude (meters)																		
	34	500	1,000	1,500	2,000	2,500	3,000	3,500	4,000	4,500	5,000	6,000	7,000	8,000	9,000	10,000	11,000	12,000	13,000
1913 July 23	12.651	10.109	9.248	6.942	5.597	4.495	3.354	2.291	1.608	1.106	0.793	0.415	0.207	0.095	0.055	0.034	0.024	0.019	0.013
24	11.363	9.740	8.808	7.562	4.993	3.871	2.976	2.329	1.820	1.441	1.162	....	....	....	....	....	0.035	0.023	0.016
27	11.949	9.687	8.708	7.288	5.003	2.852	1.661	1.301	1.064	0.839	0.581	0.289	0.118	0.040	0.017	0.009	0.006	0.003	0.003
28	10.813	8.755	7.980	5.330	3.642	2.985	2.429	1.480	1 015	0.698	0.516	0.272	0.125	0.051	0.023	0.010	0.005	0.003	0.003
29	9.933	9.372	8.913	7.645	4.711	3.056	1.964	1.163	0.674	0.384	0.265	0.112	0.060	0.019	0.011	0.006	0.002	....	....
30	12.415	11.913	10.625	6.418	5.922	4.108	2.351	1.381	0.993	0.780	0.687	0.330	0.219	0.103	0.048	0.020	0.010	0.004	0.003
31	12.952	11.261	8.640	4.717	2.379	1.434	1.444	1.210	0.855	0.580	0.344	0.193	0.118	0.062	0.034	0.014	0.007	0.004	0.002
Aug. 1	15.210	12.077	9.369	8.072	6.661	5.459	4.739	4.268	3.367	2.302	1.662	0.831	0.406	0.199	0.103	0.054	0.026	0 013	0.009
2	15.817	13.928	7.750	5.828	5.657	5.255	3.986	2.781	1.840	1.243	0.922	0.476	0.235	0.105	0.055	0.021	0.008	0.003	0.003
3	15.199	12.014	4.205	2.925	2.850	2.541	2.109	1.560	1.178	0.898	....	....	....	....	....	....	....	....	....
7	14.482	13.979	6.274	2.631	1.521	1.256	1.353	1.300	1.065	1.299	1.362	0.432	....	....	....	....	....	....	....
8	12.838	11.342	11.336	9.476	7.983	6.572	5.055	3.961	3.278	2.806	2.368	1.623	1.180	0.655	0.346	0.215	0.124	0.077	0.055
10	12.077	9.937	4.654	3.106	2.421	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Means.	12.900	11.086	8.193	5.995	4.565	3.657	2.785	2.085	1.563	1.198	0.969	0.497	0.296	0.148	0.077	0.043	0.025	0.017	0.012

Date.	Altitude (meters)																		
	14,000	15,000	16,000	17,000	18,000	19,000	20,000	21,000	22,000	23,000	24,000	25,000	26,000	27,000	28,000	29,000	30,000	31,000	32,000
1913 July 23	0.008	0.004	0.004	0.003	0.003	0.004	0.004	0.006	0.007	0.010	0.014	0.018	....	....	....	....	....	....	....
24	0.013	0.010	0.007	0.004	0.004	0.006	0.008	....	....	....	....	....	....	....	....	....	....	....	....
27	0.003	0.002	0.001	0.001	0.002	0.003	0.003	0.003	0.004	0.005	0.007	....	....	....	....	....	....	....	....
28	0.003	0.001	0.001	0.001	0.002	0.002	....	....	....	....	....	....	....	....	....	....	....	....	....
30	0.002	0.003	0.002	0.002	0.002	0.002	0.001	0.002	0.002	0.002	0.002	0.003	0.004	0.004	0.005	0.005	0.005	0.006	0.006
31	0.002	0.003	0.002	0.001	0.002	0.002	0.003	0.004	0.005	....	....	....	....	....	....	....	....	....	....
Aug. 1	0.012	0.011	0.007	0.005	0.004	0.004	0.006	0.006	0.007	0.008	....	....	....	....	....	....	....	....	....
2	0.003	0.004	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
8	0.033	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Means.	0.009	0.005	0.003	0.002	0.003	0.003	0.004	0.004	0.005	0.006	0.008	0.010	0.004	0.004	0.005	0.005	0.005	0.006	0.006

TABLE 4.—*Results of sounding balloon ascensions, Avalon, Cal.*
July 23, 1913.

Time	Altitude	Pressure	Temperature	Δt / 100 m.	Humidity Rel.	Humidity Abs.	Wind Direction	Wind Vel.	Remarks
A. M. h. m.	M.	Mm.	°C.		P. ct.	g./m.³		M.p.s.	
6 06.0	34	759.5	19.3	....	77	12.651	....	....	10/10 S. NNW.
6 08.0	489	719.8	14.3	1.1	83	10.111	N. 48° W.	1.1	
....	500	....	14.1	....	84	10.109	N. 47° W.	1.1	
6 09.1	737	699.0	12.4	0.8	92	9.972	N. 17° W.	1.0	In base of clouds. Inversion.
....	1,000	....	18.5	....	59	9.248	....	....	
6 10.2	1,032	675.0	18.9	−2.2	57	9.147	....	....	
6 12.2	1,454	642.3	17.1	0.4	49	7.068	....	....	
....	1,500	....	16.8	....	49	6.942	....	....	
....	2,000	....	12.6	....	51	5.597	....	....	
....	2,500	....	8.5	....	53	4.495	....	....	
6 17.4	2,784	547.5	6.3	0.8	54	3.975	....	....	
....	3,000	....	5.5	....	48	3.354	....	....	
6 18.9	3,194	520.8	4.9	0.3	43	2.888	....	....	
....	3,500	....	2.5	....	40	2.291	....	....	
....	4,000	....	− 1.0	....	36	1.608	....	....	
....	4,500	....	− 4.6	....	33	1.106	....	....	
6 24.5	4,719	430.1	− 6.1	0.7	31	0.919	....	....	
6 24.8	4,818	424.7	− 6.6	0.5	31	0.882	....	....	
....	5,000	....	− 7.9	....	31	0.793	....	....	
....	6,000	....	−14.7	....	29	0.415	....	....	
6 31.7	6,793	327.9	−20.0	0.7	27	0.241	....	....	
....	7,000	....	−21.6	....	27	0.207	....	....	
....	8,000	....	−29.1	....	25	0.095	....	....	
6 36.4	8,184	271.4	−30.5	0.8	25	0.082	....	....	
....	9,000	....	−34.3	....	25	0.055	....	....	
....	10,000	....	−38.8	....	25	0.034	....	....	
6 42.9	10,289	200.9	−39.9	0.4	25	0.030	....	....	
....	11,000	....	−41.4	....	24	0.024	....	....	
....	12,000	....	−43.4	....	23	0.019	....	....	
6 50.4	12,584	143.9	−44.6	0.2	22	0.016	....	....	
....	13,000	....	−46.5	....	22	0.013	....	....	
....	14,000	....	−50.6	....	21	0.008	....	....	
....	15,000	....	−54.8	....	20	0.004	....	....	
7 00.4	15,092	98.6	−55.2	0.2	20	0.004	....	....	
....	16,000	....	−55.8	....	20	0.004	....	....	
....	17,000	....	−56.6	....	20	0.003	....	....	
7 08.3	17,379	69.2	−56.9	0.1	20	0.003	....	....	Inversion.
....	18,000	....	−56.7	....	20	0.003	....	....	
....	19,000	....	−56.4	....	21	0.004	....	....	
7 15.1	19,983	46.1	−56.1	0.0	21	0.004	....	....	
....	20,000	....	−56.1	....	21	0.004	....	....	
....	21,000	....	−53.6	....	22	0.006	....	....	
....	22,000	....	−51.2	....	22	0.007	....	....	
....	23,000	....	−48.7	....	22	0.010	....	....	
....	24,000	....	−46.3	....	23	0.014	....	....	
....	25,000	....	−43.8	....	23	0.018	....	....	
7 26.8	25,160	21.5	−43.4	−0.1	23	0.019	....	....	
....	25,000	....	−43.0	....	23	0.020	....	....	
....	24,000	....	−42.1	....	21	0.020	....	....	
7 34.0	23,045	30.1	−41.1	−0.1	20	0.021	....	....	
....	23,000	....	−41.2	....	20	0.021	....	....	
....	22,000	....	−42.6	....	19	0.017	....	....	
....	21,000	....	−44.2	....	18	0.013	....	....	
7 43.9	20,314	45.0	−45.1	−0.4	17	0.011	....	....	
....	20,000	....	−46.4	....	17	0.010	....	....	
....	19,000	....	−50.5	....	17	0.006	....	....	
7 51.5	18,411	60.0	−52.8	0.5	17	0.005	....	....	Inversion.
....	18,000	....	−50.7	....	18	0.006	....	....	
7 54.2	17,857	65.3	−50.0	−0.3	18	0.007	....	....	
7 57.7	17,254	71.7	−52.1	0.1	18	0.005	....	....	Inversion.
....	17,000	....	−51.8	....	18	0.006	....	....	
....	16,000	....	−51.1	....	19	0.006	....	....	
....	15,000	....	−50.4	....	19	0.007	....	....	
8 10.9	14,285	112.3	−49.8	0.4	20	0.008	....	....	
....	14,000	....	−48.6	....	20	0.009	....	....	
....	13,000	....	−44.5	....	21	0.015	....	....	
8 18.3	12,603	144.3	−43.0	0.3	21	0.018	....	....	
....	12,000	....	−41.5	....	21	0.021	....	....	
....	11,000	....	−38.8	....	22	0.030	....	....	
....	10,000	....	−36.4	....	23	0.041	....	....	
8 31.8	9,855	214.8	−36.0	−0.5	23	0.042	....	....	
8 33.7	9,536	224.9	−37.7	0.8	23	0.035	....	....	Inversion.
....	9,000	....	−33.5	....	23	0.055	....	....	

TABLE 4.—*Results of sounding balloon ascensions, Avalon, Cal.*—Continued
July 23, 1913—Continued

Time	Altitude	Pressure	Temperature	Δt 100 m.	Humidity Rel.	Humidity Abs.	Wind Direction	Wind Vel.	Remarks
A. M. *h. m.*	*M.*	*Mm.*	°*C.*		*P. ct.*	*g./m.*^{3}		*M.p.s.*	
8 37.9	8,667	254.2	−31.0	0.8	23	0.071	....	....	
....	8,000	....	−25.8	......	25	0.129	....	....	
8 44.3	7,456	300.3	−21.6	0.5	27	0.207	....	....	
....	7,000	....	−19.4	......	28	0.265	....	....	
8 50.0	6,384	346.9	−16.4	0.6	29	0.359	....	....	
....	6,000	....	−13.8	......	30	0.464	....	....	
8 56.9	5,038	413.0	− 7.7	0.7	32	0.832	....	....	
....	5,000	....	− 7.4	......	32	0.852	....	....	
....	4,500	....	− 4.0	......	32	1.126	....	....	
....	4,000	....	− 0.7	......	32	1.464	....	....	
9 02.3	3,794	483.6	0.6	......	32	1.612	....	....	

July 24, 1913

Time	Altitude	Pressure	Temperature	Δt 100 m.	Humidity Rel.	Humidity Abs.	Wind Direction	Wind Vel.	Remarks
A. M.									
5 13.8	34	759.7	20.1	......	66	11.363	SW.......	5.9	
5 15.0	290	737.3	17.7	0.9	69	10.315	S. 26° W..	5.9	Few S. Cu. SW.
....	500	....	15.8	......	73	9.740	S. 49° W..	4.8	
5 18.1	858	689.3	13.0	0.8	79	8.887	N. 83° W..	3.1	Inversion.
....	1,000	....	14.6	......	71	8.808	S. 68° W..	2.5	
5 18.8	1,005	677.4	14.6	−1.1	70	8.684	S. 67° W..	2.4	
5 20.1	1,220	660.3	13.7	0.4	63	7.398	S. 76° W..	1.3	Inversion.
....	1,500	....	16.3	......	55	7.562	S. 31° W..	6.2	
5 21.3	1,507	638.1	16.4	−0.9	55	7.608	S. 30° W..	6.4	
5 23.9	1,925	607.5	15.1	0.3	41	5.243	S. 29° W..	7.6	
....	2,000	....	14.7	......	40	4.993	S. 29° W..	8.0	
....	2,500	....	11.4	......	38	3.871	S. 25° W..	10.0	
5 29.0	2,984	534.9	8.3	0.6	36	3.015	S. 22° W..	11.9	
....	3,000	....	8.1	......	36	2.976	S. 22° W..	12.0	
....	3,500	....	5.2	......	34	2.329	S. 37° W..	12.8	
5 33.5	3,907	477.8	2.8	0.6	32	1.870	S. 49° W..	13.4	
....	4,000	....	2.4	......	32	1.820	S. 49° W..	13.6	
....	4,500	....	− 0.5	......	31	1.441	S. 48° W..	14.3	
5 37.8	4,759	429.8	− 1.9	0.6	30	1.249	S. 48° W..	14.7	
5 38.3	4,853	424.7	− 1.9	0.0	30	1.249	S. 41° W..	21.7	
....	5,000	....	− 2.8	......	30	1.162	S. 44° W..	21.2	
5 42.1	5,588	386.9	− 6.2	0.6	29	0.852	S. 58° W..	18.9	
....	6,000	....	− 9.3	......	......	....	S. 58° W..	18.2	
5 48.2	6,968	323.4	−16.3	0.7	......	....	S. 58° W..	16.7	
....	7,000	....	−16.3	......	......	....	S. 60° W..	13.6	
5 48.8	7,114	317.0	−16.3	0.0	......	....	S. 66° W..	4.0	
5 53.1	7,999	281.8	−20.8	0.5	......	....	S. 62° W..	25.3	
....	8,000	....	−20.8	......	......	....	S. 62° W..	25.3	
....	9,000	....	−26.3	......	......	....	S. 63° W..	24.2	
5 58.5	9,171	240.2	−27.3	0.6	......	....	S. 63° W..	24.0	
....	10,000	....	−31.7	......	......	....	S. 72° W..	24.4	
6 05.2	10,423	201.6	−34.0	0.5	......	....	S. 77° W..	24.6	
....	11,000	....	−38.2	......	24	0.035	S. 72° W..	23.6	
6 08.9	11,016	185.3	−38.3	0.7	24	0.034	S. 72° W..	23.5	Few S. Cu. SW.
6 15.1	11,894	163.5	−41.8	0.4	25	0.024	S. 70° W..	19.2	
....	12,000	....	−42.4	......	25	0.023	S. 73° W..	18.7	
6 18.3	12,464	150.3	−45.1	0.6	24	0.016	S. 84° W..	16.4	
6 20.0	12,902	140.7	−45.1	0.0	24	0.016	S. 63° W..	22.2	
....	13,000	....	−45.5	......	24	0.016	S. 63° W..	20.4	
6 21.6	13,206	134.5	−46.1	0.3	24	0.014	S. 63° W..	16.1	
6 24.0	13,711	124.9	−46.0	0.0	23	0.014	S. 63° W..	18.2	
....	14,000	....	−46.6	......	23	0.013	S. 59° W..	18.4	
6 28.7	14,716	107.6	−47.9	0.2	23	0.012	S. 47° W..	18.8	
....	15,000	....	−49.6	......	23	0.010	S. 54° W..	15.7	
6 32.8	15,297	98.5	−51.3	0.6	23	0.008	S. 61° W..	12.3	
....	16,000	....	−52.2	......	23	0.007	S. 48° W..	13.2	
6 36.6	16,453	82.3	−52.8	0.1	23	0.006	S. 39° W..	13.9	
6 38.7	16,795	78.3	−55.1	0.7	22	0.005	S. 57° W..	1.7	
....	17,000	....	−55.4	......	22	0.004	S. 40° W..	3.2	
6 42.4	17,763	67.6	−55.8	0.1	22	0.004	S. 22° E...	9.0	Inversion.
....	18,000	....	−55.6	......	22	0.004	S. 74° E...	6.3	
6 45.2	18,207	63.1	−55.1	−0.1	22	0.005	N. 60° E...	4.3	Few S. Cu. SW.
6 48.0	18,511	60.2	−54.8	−0.1	23	0.005	S. 85° E...	13.9	
....	19,000	....	−53.2	......	23	0.006	S. 75° E...	10.1	
6 53.3	19,619	50.8	−51.4	−0.3	24	0.009	S. 63° E...	5.3	
....	20,000	....	−50.8	......	24	0.008	S. 4° E...	4.4	
6 57.0	20,389	45.1	−50.1	−0.2	24	0.009	S. 57° W..	3.4	Balloons disappeared.

TABLE 4.—*Results of sounding balloon ascensions, Avalon, Cal.*—Continued

July 27, 1913

Time	Altitude	Pressure	Temperature	Δt 100 m.	Humidity Rel.	Humidity Abs.	Wind Direction	Wind Vel.	Remarks
P. M. *h. m.*	*M.*	*Mm.*	*°C.*		*P. ct.*	*g./m.*³		*M.p.s.*	
4 57.5	34	759.2	20.2	......	69	11.949	S. 86° W..	3.9	2/10 S. Cu. WSW.
....	500	....	13.6	......	83	9.687	S. 80° W..	2.9	
5 00.3	704	701.3	10.9	1.4	89	8.786	S. 77° W..	2.5	Inversion.
....	1,000	....	13.3	......	76	8.708	S. 47° E...	1.0	
5 02.3	1,087	669.9	13.8	−0.8	72	8.507	S. 83° E...	0.6	
5 04.2	1,388	646.3	14.0	−0.1	65	7.775	N. 41° W..	0.8	
....	1,500	....	13.2	......	64	7.288	N. 44° W..	0.8	
5 07.0	1,912	607.0	10.0	0.8	59	5.504	N. 56° W..	1.1	
....	2,000	....	9.6	......	55	5.003	N. 87° W..	1.2	
5 09.0	2,263	581.8	8.2	0.5	44	3.661	S. 1° E...	1.6	
....	2,500	....	6.2	......	39	2.852	S..........	1.8	
5 13.0	2,980	532.8	2.5	0.8	29	1.661	S. 3° W..	2.3	
....	3,000	....	2.5	......	29	1.661	S. 7° W..	2.3	
5 15.0	3,395	505.9	0.5	0.5	27	1.351	N. 85° W..	2.2	
....	3,500	....	− 0.5	......	28	1.301	N. 86° W..	2.5	
....	4,000	....	− 4.7	......	32	1.064	S. 89° W..	3.8	
5 20.5	4,454	442.6	− 8.4	0.8	35	0.860	S. 85° W..	5.1	
....	4,500	....	− 8.7	......	35	0.839	S. 85° W..	5.2	
....	5,000	....	−13.3	......	36	0.581	S. 83° W..	6.2	
5 25.0	5,292	396.5	−15.9	0.9	37	0.478	S. 82° W..	6.7	
5 26.1	5,510	385.2	−16.3	0.2	34	0.425	S. 78° W..	8.2	
....	6,000	....	−20.5	......	34	0.289	S. 75° W..	8.3	
5 30.0	6,422	340.8	−24.1	0.9	34	0.206	S. 73° W..	8.4	
5 32.0	6,853	321.5	−27.6	0.8	31	0.133	S. 85° W..	8.7	
....	7,000	....	−29.0	......	31	0.118	S. 81° W..	8.2	
....	8,000	....	−38.4	......	28	0.040	S. 50° W..	4.6	
5 38.9	8,361	259.9	−41.7	0.9	27	0.027	S. 39° W..	3.3	
....	9,000	....	−45.1	......	26	0.017	S. 57° W..	5.2	
5 46.0	9,905	206.6	−49.9	0.5	25	0.010	S. 83° W..	8.0	
....	10,000	....	−50.2	......	25	0.009	S. 83° W..	8.3	
....	11,000	....	−53.8	......	24	0.006	S. 82° W..	12.3	
....	12,000	....	−57.4	......	23	0.003	S. 82° W..	16.3	
5 56.6	12,029	149.3	−57.5	0.4	23	0.003	S. 82° W..	16.4	Inversion.
5 59.5	12,369	141.8	−56.6	−0.3	23	0.004	N. 87° W..	7.0	
....	13,000	....	−57.5	......	23	0.003	S. 83° W..	8.3	
....	14,000	....	−58.7	......	22	0.003	S. 67° W..	9.7	
6 07.3	14,080	108.4	−58.7	0.1	22	0.003	S. 66° W..	9.9	2/10 S. Cu. WSW.
6 09.7	14,541	101.0	−61.1	0.5	21	0.002	N. 74° W..	7.4	
....	15,000	....	−61.5	......	21	0.002	N. 81° W..	7.3	
....	16,000	....	−62.2	......	21	0.001	S. 83° W..	7.0	
....	17,000	....	−63.0	......	21	0.001	S. 68° W..	6.8	
6 20.6	17,051	67.7	−63.1	0.1	21	0.001	S. 67° W..	6.8	Inversion.
....	18,000	....	−60.8	......	21	0.002	S. 2° W..	6.2	
6 28.5	18,797	51.4	−58.7	−0.3	21	0.003	S. 53° E...	5.7	
....	19,000	....	−58.7	......	21	0.003	S. 51° E...	5.3	
....	20,000	....	−57.8	......	21	0.003	S. 40° E...	3.6	
....	21,000	....	−57.0	......	21	0.003	S. 30° E...	1.9	
6 35.4	21,506	33.5	−56.5	−0.1	21	0.004	S. 25° E...	1.0	
....	22,000	....	−55.6	......	21	0.004	S. 36° E...	2.0	
....	23,000	....	−53.7	......	21	0.005	S. 59° E...	4.2	
6 41.5	23,870	23.0	−52.1	−0.1	21	0.006	S. 79° E...	6.1	Balloon burst.
....	23,000	....	−53.6	......	21	0.005	E.........	11.3	
6 44.3	22,179	29.7	−55.1	1.0	21	0.004	N. 80° E...	16.2	Inversion.
....	22,000	....	−53.5	......	21	0.005	S. 88° E...	12.4	
6 45.4	21,821	31.3	−51.5	−0.4	21	0.007	S. 76° E...	8.2	
....	21,000	....	−54.3	......	21	0.005	S. 88° E...	10.9	
6 49.0	20,229	40.2	−57.2	−0.2	21	0.003	N. 80° E...	13.6	
....	20,000	....	−57.5	......	21	0.003	N. 77° E...	12.5	
6 51.1	19,098	48.0	−59.6	0.0	19	0.002	N. 67° E...	7.8	
....	19,000	....	−59.6	......	19	0.002	N. 70° E...	7.7	
....	18,000	....	−60.0	......	19	0.002	S. 84° E...	6.6	
....	17,000	....	−60.3	......	19	0.002	S. 57° E...	5.6	
6 57.9	16,916	67.9	−60.3	−0.4	19	0.002	S. 55° E...	5.5	
7 00.0	16,284	75.3	−63.1	−0.2	20	0.001	S. 34° E...	3.7	
....	16,000	....	−63.5	......	20	0.001	W	3.6	
7 03.1	15,228	89.0	−64.7	0.1	19	0.001	N. 45° W..	3.4	Inversion.
....	15,000	....	−64.0	......	19	0.001	N. 58° W..	4.5	
7 09.0	14,178	105.3	−63.7	0.2	20	0.001	S. 76° W..	8.6	
....	14,000	....	−63.3	......	20	0.001	S. 77° W..	8.6	
7 11.9	13,498	117.5	−62.0	0.2	21	0.001	S. 79° W..	8.6	
....	13,000	....	−61.0	......	21	0.002	S. 60° W..	8.3	

TABLE 4.—*Results of sounding balloon ascensions, Avalon, Cal.*—Continued

July 27, 1913—Continued

Time	Altitude	Pressure	Temperature	Δt 100 m.	Humidity Rel.	Humidity Abs.	Wind Direction	Wind Vel.	Remarks
P. M. *h. m.*	*M.*	*Mm.*	°*C.*		*P. ct.*	*g./m³.*		*M.p.s.*	
7 15.1	12,734	132.4	−60.4	0.0	21	0.002	S. 50° W..	8.2	
7 17.0	12,323	141.4	−60.4	0.0	21	0.002	S. 62° W..	10.0	Balloons disappeared.
......	12,000	......	−60.4	......	21	0.002	......	......	
7 18.9	11,801	153.2	−60.2	0.4	21	0.002	......	......	
7 21.2	11,355	164.7	−58.5	0.6	21	0.003	......	......	
......	11,000	......	−56.2	......	21	0.004	......	......	
7 24.8	10,587	184.9	−53.6	0.8	21	0.005	......	......	
......	10,000	......	−49.1	......	22	0.010	......	......	
......	9,000	......	−41.6	......	23	0.023	......	......	
7 35.0	8,602	248.5	−38.6	0.6	24	0.033	......	......	
......	8,000	......	−35.0	......	24	0.049	......	......	
7 42.5	7,034	310.3	−29.4	0.1	25	0.092	......	......	
......	7,000	......	−29.4	......	25	0.092	......	......	
7 45.3	6,443	336.6	−28.6	0.7	30	0.117	......	......	
7 46.8	6,184	348.7	−26.9	0.5	31	0.143	......	......	
......	6,000	......	−26.0	......	33	0.167	......	......	
......	5,000	......	−20.8	......	42	0.347	......	......	
7 54.7	4,615	431.6	−18.8	2.0	46	0.460	......	......	
......	4,500	......	−16.6	......	45	0.548	......	......	
7 57.1	4,094	461.8	− 8.6	0.9	41	0.991	......	......	
......	4,000	......	− 7.8	......	41	1.057	......	......	
7 58.7	3,733	484.0	− 5.4	0.9	39	1.224	......	......	
......	3,500	......	− 3.4	......	39	1.441	......	......	
......	3,000	......	1.1	......	38	1.981	......	......	
8 04.3	2,980	532.3	1.4	0.4	38	2.021	......	......	
8 06.0	2,733	548.5	2.5	0.7	39	2.234	......	......	
......	2,500	......	4.1	......	40	2.549	......	......	
8 10.3	2,132	590.7	6.8	0.4	41	3.118	......	......	
......	2,000	......	6.3	......	49	3.607	......	......	
8 11.5	1,977	602.2	6.2	......	50	3.656	......	......	

July 28, 1913

Time	Altitude	Pressure	Temperature	Δt 100 m.	Humidity Rel.	Humidity Abs.	Wind Direction	Wind Vel.	Remarks
P. M.									
5 05.0	34	759.7	20.6	......	61	10.813	S..........	......	9/10 S. Cu. WNW.
5 06.8	371	730.3	15.8	1.4	68	9.073	S. 16° W..	3.7	
......	500	......	14.5	......	71	8.755	S. 33° W..	3.0	
5 08.7	787	694.9	11.7	1.0	77	7.991	S. 68° W..	1.5	
5 10.0	962	680.5	10.4	0.7	84	8.036	N. 67° W..	0.6	In base of S. Cu.
......	1,000	......	10.1	......	85	7.980	......	......	
5 10.9	1,117	667.8	9.7	0.5	86	7.872	......	......	Inversion.
5 11.4	1,218	659.9	15.0	−5.2	56	7.119	......	......	
5 12.3	1,377	647.4	16.2	−0.8	44	6.013	......	......	
......	1,500	......	16.2	......	39	5.330	......	......	
5 13.8	1,648	627.1	16.2	0.0	32	4.373	......	......	
5 15.2	1,923	607.1	15.4	0.3	29	3.777	......	......	
......	2,000	......	14.8	......	29	3.642	......	......	
......	2,500	......	10.0	......	32	2.985	......	......	
......	3,000	......	5.4	......	35	2.429	......	......	
5 20.3	3,048	530.1	5.0	0.9	35	2.366	......	......	
......	3,500	......	3.0	......	25	1.480	......	......	
5 22.9	3,535	499.1	3.0	0.4	24	1.421	......	......	
......	4,000	......	0.0	......	21	1.015	......	......	
5 27.4	4,498	442.6	− 2.8	0.6	18	0.698	......	......	
......	5,000	......	− 5.8	......	17	0.516	......	......	
5 31.6	5,406	394.3	− 8.1	0.6	16	0.403	......	......	
......	6,000	......	−12.7	......	16	0.272	......	......	
5 37.1	6,659	334.6	−18.1	0.8	16	0.171	......	......	
......	7,000	......	−21.4	......	16	0.125	......	......	
5 40.7	7,478	299.3	−26.3	1.0	16	0.078	......	......	
......	8,000	......	−30.7	......	16	0.051	......	......	
5 44.7	8,279	268.2	−33.0	0.8	16	0.040	......	......	
......	9,000	......	−37.8	......	15	0.023	......	......	
5 50.6	9,533	223.9	−41.5	0.7	14	0.014	......	......	
......	10,000	......	−44.7	......	14	0.010	......	......	
5 55.2	10,399	197.3	−47.2	0.7	14	0.008	......	......	
......	11,000	......	−50.6	......	14	0.005	......	......	
6 00.8	11,593	165.2	−53.6	0.5	13	0.003	......	......	

TABLE 4.—*Results of sounding balloon ascensions, Avalon, Cal.*—Continued

July 28, 1913—Continued

Time	Altitude	Pressure	Temperature	Δt 100 m.	Humidity Rel.	Humidity Abs.	Wind Direction	Wind Vel.	Remarks
P. M. *h. m.*	*M.*	*Mm.*	*°C.*		*P. ct.*	*g./m.*³		*M.p.s.*	
....	12,000	....	−55.7	......	14	0.003	....	....	
6 04.9	12,233	149.5	−56.8	0.5	14	0.002	....	....	Inversion.
....	13,000	....	−56.0	......	14	0.003	....	....	
6 09.3	13,096	131.0	−55.7	−0.1	14	0.003	....	....	Clock stopped at intervals. Time estimated.
6 11.3	13,293	127.1	−55.4	−0.2	13	0.003	....	....	
....	14,000	....	−55.7	......	13	0.003	....	....	
6 15.5	14,084	112.6	−55.7	0.0	13	0.003	....	....	Clock stopped, but started again at highest altitude.
....	19,485	48.1	−56.9	−0.1	13	0.002	....	....	
....	19,000	....	−57.5	......	13	0.002	....	....	
....	18,010	60.5	−58.8	−0.2	13	0.002	....	....	
....	18,000	....	−58.8	......	13	0.002	....	....	
....	17,000	....	−61.4	......	12	0.001	....	....	
....	16,489	77.1	−62.6	0.0	12	0.001	....	....	Inversion.
....	16,063	82.4	−62.4	0.2	12	0.001	....	....	
....	16,000	....	−62.2	......	12	0.001	....	....	
....	15,000	....	−60.1	......	13	0.001	....	....	
....	14,253	109.6	−58.5	......	13	0.002	....	....	

July 29, 1913

Time	Altitude	Pressure	Temperature	Δt 100 m.	Humidity Rel.	Humidity Abs.	Wind Direction	Wind Vel.	Remarks
A. M.									
11 10.0	34	760.5	18.6	......	63	9.933	N.86° W..	2.5	9/10 S. Cu. NW.
11 11.3	418	726.8	15.2	0.9	73	9.393	N.85° W..	2.5	
....	500	....	14.5	......	76	9.372	N.80° W..	2.3	
....	1,000	....	10.6	......	92	8.913	N.48° W..	1.3	
11 13.3	1,012	677.0	10.4	0.8	92	8.802	N.47° W..	1.2	Balloon disappeared in S. Cu. Inversion.
11 14.8	1,330	651.6	9.4	0.3	97	8.713	....	....	
....	1,500	....	11.2	......	76	7.645	....	....	
11 16.5	1,684	624.4	12.7	−0.9	55	6.073	....	....	
....	2,000	....	12.2	......	44	4.711	....	....	
11 18.4	2,182	588.3	11.9	0.2	37	3.888	....	....	
....	2,500	....	11.4	......	30	3.056	....	....	
11 20.2	2,625	557.8	11.3	0.1	27	2.733	....	....	
....	3,000	....	9.3	......	22	1.964	....	....	
11 22.9	3,344	511.4	7.4	0.5	18	1.423	....	....	
....	3,500	....	6.1	......	16	1.163	....	....	
....	4,000	....	2.2	......	12	0.674	....	....	
11 25.7	4,041	469.4	1.8	0.8	11	0.601	....	....	
....	4,500	....	− 2.9	......	10	0.384	....	....	
11 28.6	4,832	424.8	− 6.2	1.0	9	0.265	....	....	Inversion.
....	5,000	....	− 6.2	......	9	0.265	....	....	
11 29.9	5,120	409.5	− 6.1	−0.3	9	0.267	....	....	
11 33.3	5,953	367.6	−13.4	0.9	7	0.112	....	....	
....	6,000	....	−13.4	......	7	0.112	....	....	
11 35.0	6,272	352.7	−14.2	0.3	8	0.119	....	....	
11 36.1	6,629	336.2	−18.9	1.3	7	0.069	....	....	
11 37.4	6,908	324.5	−19.7	0.3	7	0.064	....	....	
....	7,000	....	−20.4	......	7	0.060	....	....	
11 39.2	7,437	301.7	−23.7	0.8	5	0.032	....	....	
11 41.0	7,882	283.7	−27.8	0.9	5	0.021	....	....	
....	8,000	....	−28.6	......	5	0.019	....	....	
11 43.2	8,570	257.7	−33.2	0.8	6	0.015	....	....	
....	9,000	....	−36.4	......	6	0.011	....	....	
11 45.0	9,029	241.7	−36.7	0.8	6	0.010	....	....	
11 45.7	9,268	233.6	−38.2	0.6	7	0.010	....	....	
11 46.8	9,467	226.9	−39.1	0.5	7	0.009	....	....	
11 47.9	9,707	218.9	−42.5	1.4	7	0.006	....	....	Inversion.
11 48.1	9,928	212.2	−42.1	−0.2	7	0.007	....	....	
....	10,000	....	−43.4	......	7	0.006	....	....	
11 49.4	10,248	202.8	−47.2	1.6	6	0.003	....	....	Inversion. One balloon burst and was detached; remaining balloon had sufficient lifting force to continue ascent.
11 53.0	10,633	191.3	−46.9	−0.8	......	....	....	....	
11 53.8	10,747	188.2	−47.3	0.4	......	....	....	....	
11 53.9	10,794	186.5	−48.3	2.1	......	....	....	....	
11 55.0	10,915	183.3	−48.7	0.3	......	....	....	....	Clock stopped.
....	*11,000	....	*−49.3	......	*5	0.002	....	....	

* Estimated by extrapolation from the ascent.

TABLE 4.—*Results of sounding balloon ascensions, Avalon, Cal.*—Continued

July 29, 1913—Continued

Time	Altitude	Pressure	Temperature	Δt 100 m.	Humidity Rel.	Humidity Abs.	Wind Direction	Wind Vel.	Remarks
A. M.									
h. m.	*M.*	*Mm.*	*°C.*		*P. ct.*	*g./m.³*		*M.p.s.*	
...	*23,066	27.8	−44.3	−0.4	...	...	...	...	Balloon burst.
...	23,000	...	−44.5	...	...	...	...	...	
...	22,000	...	−49.5	...	...	...	...	...	
...	21,305	36.3	−53.0	−0.2	...	...	...	...	
...	21,000	...	−53.5	...	...	...	...	...	
...	20,000	...	−55.2	...	...	...	...	...	
...	19,000	...	−56.7	...	...	...	...	...	
...	18,111	59.7	−58.4	0.0	...	...	...	...	
...	18,000	...	−58.3	...	...	...	...	...	
...	17,145	69.5	−58.5	−0.2	...	...	...	...	
...	17,000	...	−58.7	...	...	...	...	...	
...	16,141	81.4	−60.4	0.1	...	...	...	...	Inversion.
...	16,000	...	−60.2	...	...	...	...	...	
...	15,000	...	−59.2	...	...	...	...	...	
...	14,344	107.9	−58.3	0.1	3	0.001	...	...	
...	14,000	...	−58.3	...	3	0.001	...	...	
...	13,000	...	−57.6	...	3	0.001	...	...	
...	12,386	146.6	−57.3	0.0	3	0.001	...	...	
...	12,000	...	−57.3	...	3	0.001	...	...	
...	11,368	170.9	−57.3	...	4	0.001	...	...	
...	11,000	...	−50.4	...	5	0.002	...	...	

*Balloon burst; clock started running, but times of this and succeeding levels unknown.

July 30, 1913

Time	Altitude	Pressure	Temperature	Δt 100 m.	Humidity Rel.	Humidity Abs.	Wind Direction	Wind Vel.	Remarks
A. M.									
10 54.0	34	760.0	23.0	...	61	12.415	NE...	...	Few Cu.
10 57.0	362	731.7	21.0	0.6	67	12.155	SE...	...	
...	500	...	19.9	...	70	11.913	S...	...	
11 01.0	695	703.8	18.3	0.8	74	11.463	S. 50° W..	0.6	
11 03.0	884	688.3	16.9	0.7	80	11.402	S. 56° W..	1.8	Inversion.
...	1,000	...	18.2	...	69	10.625	S. 1° W..	1.9	
11 06.0	1,184	664.5	19.9	−1.0	54	9.190	S. 86° W..	2.1	
11 07.3	1,338	652.7	20.4	−0.3	40	7.008	S. 42° E...	5.1	
...	1,500	...	20.7	...	36	6.418	S. 38° E...	6.4	
11 12.3	1,766	621.1	21.3	−0.2	29	5.353	S. 32° E...	8.7	
11 13.9	1,927	609.5	20.7	0.4	26	4.636	S. 42° E...	12.8	
...	2,000	...	20.3	...	34	5.922	S. 38° E...	12.4	
11 15.0	2,045	601.3	20.2	0.4	38	6.581	S. 35° E...	12.1	
11 16.9	2,185	591.5	19.6	0.4	45	7.525	S. 33° E...	15.8	Inversion.
11 18.9	2,413	576.7	20.4	−0.4	30	5.256	S. 32° E...	15.2	
11 20.0	2,499	570.3	20.1	0.3	24	4.132	S. 33° E...	14.8	
...	2,500	...	20.0	...	24	4.108	S. 33° E...	14.8	
...	3,000	...	18.5	...	15	2.351	S. 25° E...	16.0	
11 26.0	3,067	532.9	18.3	0.3	14	2.169	S. 24° E...	16.2	
11 29.0	3,339	516.7	16.1	0.8	11	1.494	S. 14° E...	17.8	
...	3,500	...	14.8	...	11	1.381	S. 14° E...	17.2	
...	4,000	...	11.0	...	10	0.993	S. 16° E...	15.4	
11 37.0	4,133	470.1	10.2	0.7	10	0.945	S. 16° E...	15.0	
11 39.0	4,362	457.3	8.2	0.9	10	0.832	S. 18° E...	17.1	Balloon disappeared.
...	4,500	...	7.2	...	10	0.780	...	...	Few Cu.
...	5,000	...	3.8	...	11	0.687	...	...	
11 45.0	5,157	414.9	2.7	0.7	12	0.697	...	...	
11 49.3	5,749	385.4	− 1.1	0.6	9	0.399	...	...	
...	6,000	...	− 3.5	...	9	0.330	...	...	
11 53.0	6,273	360.8	− 6.1	1.0	10	0.296	...	...	
11 55.5	6,672	342.7	− 9.2	0.8	10	0.230	...	...	
...	7,000	...	− 9.8	...	10	0.219	...	...	
11 58.5	7,093	324.5	− 9.9	0.2	10	0.217	...	...	
P. M.									
12 01.0	7,475	309.1	−12.2	0.6	8	0.142	...	...	
...	8,000	...	−15.9	...	8	0.103	...	...	
12 09.0	8,915	255.1	−22.1	0.7	7	0.051	...	...	
...	9,000	...	−22.8	...	7	0.048	...	...	
...	10,000	...	−30.2	...	6	0.020	...	...	
12 16.0	10,323	210.3	−32.6	0.7	6	0.016	...	...	Inversion.
12 17.0	10,521	204.6	−32.4	−0.1	6	0.016	...	...	
12 18.8	10,832	195.7	−35.6	1.0	6	0.012	...	...	

TABLE 4.—*Results of sounding balloon ascensions, Avalon, Cal.*—Continued.

July 30, 1913—Continued

Time	Altitude	Pressure	Temperature	Δt / 100 m.	Humidity: Rel.	Humidity: Abs.	Wind: Direction	Wind: Vel.	Remarks
P. M. h. m.	M.	Mm.	°C.		P. ct.	g./m.³		M.p.s.	
....	11,000	....	−37.3	......	6	0.010	....	....	
12 22.9	11,724	172.1	−43.6	0.9	6	0.005	....	....	
....	12,000	....	−44.2	......	6	0.004	....	....	
12 25.3	12,391	156.1	−44.9	0.2	6	0.004	....	....	
12 26.8	12,653	150.2	−48.4	1.3	6	0.003	....	....	
....	13,000	....	−49.1	......	6	0.003	....	....	
....	14,000	....	−51.3	......	6	0.002	....	....	
12 32.1	14,021	122.5	−51.3	0.2	6	0.002	....	....	Inversion.
....	15,000	....	−49.2	......	6	0.003	....	....	
12 37.0	15,241	102.1	−48.6	−0.2	6	0.003	....	....	
12 37.8	15,435	99.3	−51.4	1.4	6	0.002	....	....	
....	16,000	....	−50.3	......	6	0.002	....	....	
12 42.3	16,707	81.8	−49.0	0.2	6	0.003	....	....	
....	17,000	....	−49.8	......	6	0.002	....	....	
....	18,000	....	−53.0	......	6	0.002	....	....	
12 47.2	18,263	64.7	−53.9	0.3	6	0.001	....	....	Inversion.
12 50.1	18,877	58.9	−50.5	−0.6	5	0.002	....	....	
....	19,000	....	−50.7	......	5	0.002	....	....	
....	20,000	....	−52.3	......	5	0.001	....	....	
12 53.7	20,131	48.8	−52.5	0.2	5	0.001	....	....	Inversion.
....	21,000	....	−51.4	......	5	0.002	....	....	
....	22,000	....	−50.2	......	5	0.002	....	....	
....	23,000	....	−49.0	......	5	0.002	....	....	
1 01.8	23,005	31.5	−49.0	−0.1	5	0.002	....	....	
1 03.9	23,932	27.3	−49.5	0.1	5	0.002	....	....	Inversion.
....	24,000	....	−49.4	......	5	0.002	....	....	
....	25,000	....	−47.7	......	5	0.003	....	....	
....	26,000	....	−46.2	......	6	0.004	....	....	
....	27,000	....	−44.5	......	6	0.004	....	....	
....	28,000	....	−42.8	......	6	0.005	....	....	
1 11.0	28,062	14.7	−42.7	−0.2	6	0.005	....	....	
....	29,000	....	−42.5	......	6	0.005	....	....	
....	30,000	....	−42.4	......	6	0.005	....	....	
....	31,000	....	−42.1	......	6	0.006	....	....	
....	32,000	....	−41.9	......	6	0.006	....	....	
1 20.5	32,643	7.4	−41.8	0.0	6	0.006	....	....	
....	32,000	....	−42.1	......	6	0.006	....	....	
....	31,000	....	−42.9	......	6	0.005	....	....	
....	30,000	....	−43.4	......	5	0.004	....	....	
....	29,000	....	−44.0	......	5	0.004	....	....	
....	28,000	....	−44.7	......	5	0.003	....	....	
....	27,000	....	−45.4	......	5	0.003	....	....	
....	26,000	....	−46.0	......	5	0.003	....	....	
1 24.9	25,118	22.7	−46.6	−0.1	3	0.003	....	....	
....	25,000	....	−46.8	......	5	0.003	....	....	
....	24,000	....	−49.4	......	5	0.002	....	....	
....	23,000	....	−50.8	......	5	0.002	....	....	
(*)	22,249	35.1	−52.3	0.0	5	0.001	....	....	
....	22,000	....	−52.4	......	5	0.001	....	....	
....	21,000	....	−52.6	......	5	0.001	....	....	
....	20,000	....	−53.0	......	5	0.001	....	....	
....	19,051	57.2	−53.3	0.1	5	0.001	....	....	Inversion.
....	19,000	....	−53.2	......	5	0.001	....	....	
....	18,000	....	−52.4	......	5	0.001	....	....	
....	17,000	....	−51.5	......	6	0.002	....	....	
....	16,160	88.6	−50.8	......	6	0.002	....	....	
....	16,000	....	−50.6	......	6	0.002	....	....	

* Clock stopped at intervals; times of this and subsequent levels unknown.

July 31, 1913

Time	Altitude	Pressure	Temperature	Δt / 100 m.	Humidity: Rel.	Humidity: Abs.	Wind: Direction	Wind: Vel.	Remarks
A. M.									
10 37.5	34	762.0	22.9	......	64	12.952	....	....	5/10 Ci. S.
10 39.3	388	731.3	18.0	1.4	74	11.261	....	....	
....	500	....	18.0	......	74	11.261	....	....	
10 40.2	622	711.5	18.1	0.0	74	11.328	....	....	Inversion.
10 41.0	799	696.9	20.5	−1.4	63	11.102	S. 69° E..	1.5	

TABLE 4.—*Results of sounding balloon ascensions, Avalon, Cal.*—Continued

July 31, 1913—Continued

Time	Altitude	Pressure	Temperature	Δt / 100 m.	Humidity Rel.	Humidity Abs.	Wind Direction	Wind Vel.	Remarks
A. M. h. m.	M.	Mm.	°C.		P. ct.	g./m.³		M.p.s.	
10 41.8	995	681.2	21.7	—0.6	46	8.690	S. 57° E...	5.6	
....	1,000	....	21.6	......	46	8.640	S. 57° E...	5.6	
10 43.2	1,403	649.7	21.7	0.0	28	5.289	S. 58° E...	6.5	
....	1,500	....	21.0	......	26	4.717	S. 52° E...	6.2	
10 45.6	1,898	613.4	19.2	0.5	16	2.613	S. 29° E...	5.1	
....	2,000	....	18.7	......	15	2.379	S. 24° E...	5.8	
10 47.3	2,354	581.4	17.0	0.5	10	1.434	S. 8° E...	8.5	
....	2,500	....	17.0	......	10	1.434	S. 20° E...	10.8	
10 48.3	2,542	568.6	17.0	0.0	10	1.434	S. 23° E...	11.5	
....	3,000	....	12.8	......	13	1.444	S. 25° E...	9.4	
10 50.2	3,109	531.7	12.0	0.9	13	1.375	S. 25° E...	8.9	
....	3,500	....	8.8	......	14	1.210	S. 22° E...	8.0	
10 52.0	3,588	501.7	8.1	0.8	14	1.158	S. 21° E...	7.7	
....	4,000	....	5.8	......	12	0.855	S. 27° E...	11.2	
10 54.5	4,418	456.2	3.7	0.5	10	0.620	S. 33° E...	15.0	
....	4,500	....	2.7	......	10	0.580	S. 33° E...	14.6	
....	5,000	....	— 1.5	......	8	0.344	S. 34° E...	12.8	
10 57.3	5,041	419.5	— 1.8	0.9	8	0.336	S. 34° E...	12.7	
11 00.2	5,795	381.0	— 9.3	1.0	9	0.205	S. 36° E...	13.7	
....	6,000	....	—11.3	......	10	0.193	S. 35° E...	14.6	
11 03.0	6,557	345.2	—16.7	1.0	12	0.145	S. 32° E...	16.9	
....	7,000	....	—20.6	......	14	0.118	S. 26° E...	16.2	
11 06.0	7,430	307.0	—24.4	0.9	16	0.094	S. 20° E...	15.7	
....	8,000	....	—28.6	......	16	0.062	S. 10° E...	14.4	
11 09.0	8,384	269.1	—31.3	0.7	16	0.048	S. 4° E...	13.6	Balloons disappeared in Cirrus clouds.
11 10.0	8,781	254.9	—32.8	0.4	16	0.041	....	....	
....	9,000	....	—34.6	......	16	0.034	....	....	
....	10,000	....	—42.2	......	15	0.014	....	....	
11 13.8	10,188	208.4	—43.6	0.8	15	0.012	....	....	5/10 Ci. S.
....	11,000	....	—47.4	......	14	0.007	....	....	
11 18.2	11,725	166.0	—51.1	0.5	14	0.005	....	....	
....	12,000	....	—52.3	......	14	0.004	....	....	
....	13,000	....	—56.9	......	13	0.002	....	....	
11 21.2	13,165	132.9	—57.6	0.5	13	0.002	....	....	
11 22.6	13,533	126.0	—58.5	0.2	13	0.002	....	....	Inversion.
....	14,000	....	—56.7	......	12	0.002	....	....	
11 23.9	14,154	114.2	—56.1	—0.4	12	0.002	....	....	
11 25.4	14,646	106.0	—54.5	—0.3	14	0.003	....	....	
....	15,000	....	—55.4	......	14	0.003	....	....	
....	16,000	....	—57.7	......	12	0.002	....	....	
11 29.6	16,166	83.7	—58.1	0.2	12	0.002	....	....	
11 30.1	16,600	78.1	—58.8	0.2	12	0.001	....	....	Inversion.
11 31.3	16,933	74.4	—58.4	—0.1	12	0.002	....	....	
....	17,000	....	—58.6	......	12	0.001	....	....	
11 31.8	17,134	72.0	—58.9	0.2	12	0.001	....	....	Inversion.
....	18,000	....	—58.0	......	12	0.002	....	....	
11 34.8	18,607	57.1	—57.6	—0.1	12	0.002	....	....	
....	19,000	....	—56.4	......	13	0.002	....	....	
11 36.4	19,580	49.1	—54.6	—0.3	13	0.003	....	....	
....	20,000	....	—53.7	......	13	0.003	....	....	
....	21,000	....	—51.9	......	13	0.004	....	....	
11 40.3	21,352	37.4	—51.2	—0.2	13	0.004	....	....	
11 41.5	21,557	36.2	—51.3	0.1	12	0.004	....	....	Inversion.
....	22,000	....	—49.8	......	13	0.005	....	....	
11 43.0	22,194	32.5	—48.6	—0.4	13	0.006	....	....	

August 1, 1913

Time	Altitude	Pressure	Temperature	Δt / 100 m.	Humidity Rel.	Humidity Abs.	Wind Direction	Wind Vel.	Remarks
A. M.									
10 36.0	34	761.0	23.9	......	71	15.210	....	....	4/10 Ci. S.
10 36.8	179	748.4	20.0	2.7	74	12.667	....	....	Inversion.
10 38.0	365	732.4	22.4	—1.3	66	12.980	....	....	
....	500	....	23.1	......	59	12.077	....	....	
10 40.0	707	704.1	24.4	—0.6	46	10,137	S. 8° W..	0.5	
10 40.9	859	691.8	24.7	—0.2	44	9.862	S. 44° E...	2.6	
....	1,000	....	24.2	......	43	9.369	S. 39° E...	6.6	
10 41.9	1,015	679.6	24.2	0.3	42	9.151	S. 38° E...	7.3	
....	1,500	....	22.0	......	42	8.072	S. 42° E...	8.1	

TABLE 4.—*Results of sounding balloon ascensions, Avalon, Cal.*—Continued

August 1, 1913—Continued

Time	Altitude	Pressure	Temperature	Δt 100 m.	Humidity Rel.	Humidity Abs.	Wind Direction	Wind Vel.	Remarks
A. M. *h. m.*	*M.*	*Mm.*	°*C.*		*P. ct.*	*g./m.*^{3}		*M.p.s.*	
10 44.9	1,534	640.0	21.8	0.5	42	7.980	S. 42° E...	8.2	
....	2,000	....	18.3	......	43	6.661	S. 43° E...	7.0	
....	2,500	....	14.6	......	44	5.459	S. 44° E...	5.7	
10 51.1	2,555	567.8	14.0	0.8	44	5.263	S. 44° E...	5.5	
....	3,000	....	10.9	......	48	4.739	S. 36° E...	6.1	
....	3,500	....	7.4	......	54	4.268	S. 28° E...	6.7	
....	4,000	....	3.6	......	59	3.367	S. 19° E...	7.4	
10 58.8	4,238	468.7	2.2	0.7	61	3.424	S. 15° E...	7.7	
11 00.7	4,432	451.7	1.9	0.2	44	2.420	S. 4° E...	8.3	
....	4,500	....	1.5	......	43	2.302	S. 3° E...	8.5	
....	5,000	....	− 1.6	......	39	1.662	S..........	10.3	
11 05.5	5,381	400.9	− 4.0	0.6	36	1.266	S. 3° W..	11.6	
....	6,000	....	− 9.5	......	37	0.831	S. 7° E...	10.1	
11 09.8	6,233	359.7	−11.6	0.8	37	0.694	S. 12° E...	9.5	Inversion.
11 10.4	6,296	356.7	−10.8	−1.3	38	0.765	S. 8° W..	15.6	
11 11.2	6,426	350.6	−13.7	2.2	37	0.576	S. 12° W..	14.8	
11 12.8	6,880	330.7	−16.8	0.7	37	0.443	S. 6° W..	16.0	
....	7,000	....	−17.5	......	36	0.406	S. 1° E...	12.5	
11 14.9	7,218	315.8	−18.2	0.4	35	0.371	S. 13° E...	6.6	
....	8,000	....	−23.5	......	31	0.199	S. 6° E. .	8.3	
11 19.2	8,138	279.1	−24.3	0.7	30	0.178	S. 5° E...	8.6	
....	9,000	....	−30.0	......	30	0.103	S. 2° E...	11.3	
....	10,000	....	−36.6	......	31	0.054	S. 1° W..	14.3	
11 29.3	10,703	184.6	−41.4	0.7	31	0.031	S. 3° W..	16.5	Balloon disappeared in Ci.
....	11,000	....	−43.2	......	31	0.026	....	....	
11 34.5	11,966	161.7	−49.5	0.6	31	0.013	....	....	
....	12,000	....	−49.4	......	31	0.013	....	....	
11 36.0	12,366	152.5	−49.8	0.1	30	0.012	....	....	
11 37.2	12,827	142.1	−52.4	0.6	30	0.009	....	....	
....	13,000	....	−52.3	......	30	0.009	....	....	
11 40.8	13,650	125.4	−52.4	0.0	31	0.009	....	....	Inversion.
11 42.7	13,977	119.4	−49.8	−0.8	31	0.012	....	....	
....	14,000	....	−49.8	......	31	0.012	....	....	
11 45.2	14,778	106.0	−49.8	0.0	30	0.012	....	....	
....	15,000	....	−50.5	......	30	0.011	....	....	
....	16,000	....	−54.0	......	29	0.007	....	....	
11 53.9	16,717	78.7	−56.4	0.3	28	0.005	....	....	Inversion.
11 55.2	16,849	77.1	−55.5	−0.7	28	0.006	....	....	
....	17,000	....	−56.0	......	28	0.005	....	....	
11 57.0	17,493	69.7	−57.3	0.3	28	0.004	....	....	
....	18,000	....	−58.0	......	28	0.004	....	....	
12 00.0	18,395	60.6	−58.6	0.1	28	0.003	....	....	Inversion.
....	19,000	....	−57.6	......	29	0.004	....	....	
P. M.									
12 03.3	19,993	47.3	−56.2	−0.2	30	0.006	....	....	
....	20,000	....	−56.2	......	30	0.006	....	....	
12 06.0	20,195	45.7	−55.9	−0.1	30	0.006	....	....	
12 06.7	20,451	44.1	−54.2	−0.7	30	0.007	....	....	
12 07.2	20,675	42.6	−55.4	0.5	30	0.006	....	....	
....	21,000	....	−55.0	......	30	0.006	....	....	
....	22,000	....	−54.3	......	30	0.007	....	....	
....	23,000	....	−53.5	......	30	0.008	....	....	
12 11.3	23,466	27.7	−53.1	0.2	30	0.008	....	....	
....	23,000	....	−51.5	......	29	0.009	....	....	
12 12.6	22,792	30.8	−50.7	−0.1	28	0.010	....	....	
....	22,000	....	−51.4	......	28	0.009	....	....	
12 15.6	21,226	38.7	−52.0	−0.2	28	0.008	....	....	
....	21,000	....	−52.5	......	28	0.008	....	....	
....	20,000	....	−55.0	......	28	0.006	....	....	
12 17.7	19,666	49.8	−55.7	0.4	28	0.006	....	....	Inversion.
12 18.7	19,273	52.9	−54.0	−0.1	28	0.007	....	....	
12 19.3	19,133	54.1	−55.4	−0.4	28	0.006	....	....	
....	19,000	....	−55.7	......	28	0.006	....	....	
12 21.2	18,592	58.8	−57.3	0.4	28	0.004	....	....	Inversion.
....	18,000	....	−54.6	......	29	0.007	....	....	
12 23.0	17,483	69.8	−52.4	−0.5	29	0.008	....	....	
12 25.3	17,054	74.6	−54.8	0.3	28	0.006	....	....	Inversion.
....	17,000	....	−54.6	......	28	0.006	....	....	
12 25.7	16,773	77.7	−54.0	−0.2	28	0.007	....	....	

TABLE 4.—*Results of sounding balloon ascensions, Avalon, Cal.*—Continued

August 1, 1913—Continued

Time	Altitude	Pressure	Temperature	Δt / 100 m.	Humidity Rel.	Humidity Abs.	Wind Direction	Wind Vel.	Remarks
P. M. *h. m.*	*M.*	*Mm.*	°*C.*		*P. ct.*	*g./m.*³		*M.p.s.*	
12 26.5	16,414	82.0	−54.8	0.2	29	0.006	....	....	Inversion.
....	16,000	....	−53.8	......	29	0.007	....	....	
....	15,000	....	−51.4	......	29	0.009	....	....	
12 32.4	14,227	114.8	−49.5	−0.2	29	0.012	....	....	
....	14,000	....	−50.0	......	29	0.011	....	....	
12 34.5	13,254	132.9	−51.5	0.1	28	0.009	....	....	Inversion.
....	13,000	....	−51.3	......	28	0.009	....	....	
12 37.6	12,441	150.0	−50.7	0.4	......	......	....	....	
....	12,000	....	−48.9	......	30	0.013	....	....	
....	11,000	....	−44.9	......	33	0.023	....	....	
12 42.0	10,857	190.0	−44.4	0.1	33	0.024	....	....	
....	10,000	....	−37.9	......	35	0.052	....	....	
12 47.5	9,303	237.2	−32.7	0.8	37	0.096	....	....	
....	9,000	....	−30.5	......	36	0.118	....	....	
12 51.7	8,188	276.8	−24.3	0.5	33	0.196	....	....	
....	8,000	....	−23.5	......	33	0.212	....	....	
12 55.9	7,058	322.6	−19.2	0.9	34	0.328	....	....	
....	7,000	....	−18.7	......	34	0.343	....	....	
....	6,000	....	−10.2	......	36	0.762	....	....	
1 00.4	5,719	384.0	− 7.7	0.7	36	0.936	....	....	
1 02.8	5,115	414.9	− 3.6	......	......	......	....	....	
....	5,000	....	− 3.0	......	37	1.411	....	....	

August 2, 1913

Time	Altitude	Pressure	Temperature	Δt / 100 m.	Humidity Rel.	Humidity Abs.	Wind Direction	Wind Vel.	Remarks
A. M.									
10 59.0	34	761.0	25.1	......	69	15.817	E........	....	Inversion.
11 00.3	259	741.5	22.8	1.0	71	14.287	....	....	Cloudless.
11 01.5	437	726.5	26.7	−2.2	59	14.788	....	....	
....	500	....	27.9	......	52	13.928	....	....	
11 02.7	584	714.5	29.0	−1.6	45	12.801	....	....	
11 04.0	753	701.0	30.0	−0.6	34	10.212	S. 83° W..	1.1	
11 05.0	907	689.0	29.0	0.6	29	8.250	S. 64° W..	3.3	
....	1,000	....	28.5	......	28	7.750	S. 13° E...	2.3	
11 06.0	1,059	677.1	28.1	0.6	27	7.312	S. 62° E...	1.5	
11 07.0	1,197	666.6	27.4	0.5	24	6.253	S. 47° W..	3.7	
....	1,500	....	25.4	......	25	5.828	S. 21° E...	3.3	
11 10.0	1,618	635.3	24.7	0.6	25	5.603	S. 48° E...	3.1	
....	2,000	....	21.1	......	31	5.657	S. 33° E...	4.1	
11 14.5	2,289	587.7	18.4	0.9	35	5.454	S. 21° E...	4.9	Inversion.
11 14.9	2,328	584.7	19.1	−1.8	35	5.683	S. 12° E...	4.6	
....	2,500	....	17.3	......	36	5.255	S. 9° E...	5.2	
....	3,000	....	12.3	......	37	3.986	S. 1° E...	7.2	
11 19.6	3,015	539.0	12.2	1.0	37	3.961	S. 1° E...	7.3	Inversion.
11 20.0	3,053	536.2	12.6	−1.1	37	4.060	S. 7° E...	18.8	
11 22.0	3,307	520.1	10.6	0.8	33	3.197	S. 21° E...	7.2	
....	3,500	....	9.9	......	30	2.781	S. 10° E...	7.4	
11 24.0	3,661	498.3	9.2	0.4	28	2.483	S. 1° E...	7.5	
....	4,000	....	6.3	......	25	1.840	S. 6° E...	9.2	
11 29.0	4,437	453.2	2.9	0.8	22	1.294	S. 13° E...	11.4	
....	4,500	....	2.3	......	22	1.243	S. 12° E...	11.2	
....	5,000	....	− 0.6	......	20	0.922	S. 8° E...	10.4	
11 36.3	5,717	386.1	− 4.6	0.6	18	0.603	S. 2° E...	9.0	
....	6,000	....	− 6.8	......	17	0.476	S........	9.0	
11 42.5	6,789	336.8	−12.7	0.8	16	0.272	S. 7° W..	9.2	
....	7,000	....	−14.4	......	16	0.235	S. 5° W..	9.6	
11 48.0	7,912	289.8	−21.7	0.8	15	0.114	S. 4° E...	11.6	
....	8,000	....	−22.5	......	15	0.105	S. 2° E...	11.5	
....	9,000	....	−28.5	......	14	0.055	S. 21° W..	11.0	
11 53.2	9,086	247.1	−29.0	0.6	14	0.053	S. 23° W..	10.9	
....	10,000	....	−37.1	......	13	0.021	S. 26° W..	10.8	
12 00.0	10,591	199.3	−42.2	0.9	13	0.012	S. 28° W..	10.7	
P. M.									
....	11,000	....	−45.6	......	13	0.008	S. 29° W..	11.0	
....	12,000	....	−54.0	......	12	0.003	S. 30° W..	11.8	
12 05.5	12,031	161.1	−54.4	0.8	12	0.003	S. 30° W..	11.8	
....	13,000	....	−55.2	......	13	0.003	S. 21° W..	21.7	
12 09.4	13,168	135.4	−55.3	0.8	13	0.003	S. 20° W..	23.3	Inversion.

TABLE 4.—*Results of sounding balloon ascensions, Avalon, Cal.*—Continued

August 2, 1913—Continued

Time	Altitude	Pressure	Temperature	Δt 100 m.	Humidity Rel.	Humidity Abs.	Wind Direction	Wind Vel.	Remarks
P. M. *h. m.*	*M.*	*Mm.*	*°C.*		*P. ct.*	*g./m.³*		*M.p.s.*	
12 11.0	13,449	130.0	−54.0	−0.5	13	0.003	S. 8° W.	19.3	
12 12.5	13,815	122.7	−55.0	0.3	13	0.003	S. 8° W.	24.3	Inversion.
....	14,000	....	−54.1	.....	13	0.003	S. 8° W.	23.0	
12 14.1	14,284	114.4	−52.8	−0.5	13	0.004	S. 8° W.	20.8	
12 16.1	14,541	110.1	−54.1	0.5	12	0.003	S. 31° W.	18.3	Inversion. One balloon burst and became detached; the remaining balloon had sufficient lifting force to continue ascent.
12 17.3	14,799	105.7	−50.3	−1.5	12	0.005	S. 50° W.	14.7	
....	15,000	....	−50.9	.....	12	0.004	S. 44° W.	18.4	
12 22.6	15,437	96.0	−52.1	0.3	12	0.004	S. 30° W.	27.2	
....	16,000	....	....	.....	.....	....	S. 4° E.	19.7	
12 32.0	*16,890	....	....	.....	.....	....	S. 59° E.	7.4	Balloon disappeared. Few Cu.
12 56.4	21,302	35.5	−40.0	−0.5	10	0.012	....	....	
....	21,000	....	−42.5	.....	10	0.009	....	....	
....	20,000	....	−50.6	.....	10	0.004	....	....	
....	19,000	....	−58.8	.....	10	0.001	....	....	
12 57.9	18,990	53.9	−58.7	−0.3	10	0.001	....	....	
....	18,000	....	−61.8	.....	10	0.001	....	....	
....	17,000	....	−63.9	.....	10	0.001	....	....	
....	16,000	....	−66.6	.....	10	0.001	....	....	
1 00.0	15,828	89.0	−67.3	0.5	10	0.001	....	....	Inversion.
....	15,000	....	−63.2	.....	11	0.001	....	....	
....	14,000	....	−58.5	.....	13	0.002	....	....	
1 01.8	13,908	120.5	−58.0	0.0	13	0.002	....	....	
....	13,000	....	−57.6	.....	13	0.002	....	....	
....	12,000	....	−57.3	.....	13	0.002	....	....	
1 03.3	11,896	164.5	−57.1	.....	13	0.002	....	....	

*Clock stopped. Altitude computed from ascensional rate.

August 3, 1913

Time	Altitude	Pressure	Temperature	Δt 100 m.	Humidity Rel.	Humidity Abs.	Wind Direction	Wind Vel.	Remarks
P. M. 5 07.0	34	756.9	26.3	.....	62	15.199	....	....	Few Cu. over mountains on mainland. Inversion.
5 07.7	233	739.8	24.1	1.1	62	13.433	....	....	
....	500	....	30.0	.....	40	12.014	....	....	
5 09.4	541	714.4	30.8	−2.2	37	11.604	....	....	
5 10.3	754	697.5	30.3	0.2	25	7.632	N. 65° W.	2.7	
5 11.3	879	687.7	30.6	−0.2	18	5.585	N. 65° W.	6.4	
....	1,000	....	30.0	.....	14	4.205	N. 62° W.	5.8	
5 13.0	1,079	672.3	29.5	0.5	11	3.216	N. 60° W.	5.4	
5 14.0	1,284	656.9	28.1	0.7	11	2.979	S. 81° W.	5.3	
....	1,500	....	26.2	.....	12	2.925	S. 75° W.	5.0	
....	2,000	....	21.8	.....	15	2.850	S. 60° W.	4.5	
5 19.9	2,398	577.7	18.4	0.9	17	2.649	S. 49° W.	4.0	
....	2,500	....	17.7	.....	17	2.541	S. 46° W.	4.2	
5 22.8	2,838	548.7	15.8	0.6	17	2.268	S. 36° W.	4.9	
....	3,000	....	14.6	.....	17	2.109	S. 25° W.	5.2	
....	3,500	....	10.7	.....	16	1.560	S. 9° E.	6.1	
5 28.0	3,804	488.8	8.4	0.8	15	1.264	S. 30° E.	6.6	
....	4,000	....	7.3	.....	15	1.178	S. 9° E.	5.2	
5 31.0	4,459	451.3	4.5	0.6	14	0.916	S. 39° W.	1.8	
....	4,500	....	4.2	.....	14	0.898	S. 42° W.	1.8	
5 34.0	4,996	422.0	− 0.2	0.9	.....	....	S. 73° W.	2.2	
....	5,000	....	− 0.5	.....	.....	....	S. 73° W.	2.3	
5 37.0	5,533	394.7	− 3.8	0.7	.....	....	S. 79° W.	4.8	
5 39.0	5,792	381.8	− 6.6	1.1	.....	....	S. 48° W.	4.6	
....	6,000	....	− 8.2	.....	.....	....	S. 44° W.	4.2	
....	7,000	....	−17.0	.....	.....	....	S. 22° W.	2.5	
5 45.8	7,183	318.9	−17.4	0.8	.....	....	S. 18° W.	2.2	
....	8,000	....	−24.5	.....	.....	....	S.	3.5	
5 52.0	8,308	273.7	−27.2	0.9	.....	....	S. 7° E.	4.0	
....	9,000	....	−31.1	.....	.....	....	S.	5.9	
5 58.0	9,573	229.7	−34.4	0.6	.....	....	S. 6° W.	7.6	
....	10,000	....	−36.8	.....	.....	....	S. 7° W.	7.7	
6 04.8	10,790	193.0	−41.5	0.6	.....	....	S. 8° S.	7.9	
....	11,000	....	−42.7	.....	.....	....	S. 9° W.	9.4	

TABLE 4.—*Results of sounding balloon ascensions, Avalon, Cal.*—Continued

August 3, 1913—Continued

Time	Altitude	Pressure	Temperature	Δt 100 m.	Humidity Rel.	Humidity Abs.	Wind Direction	Wind Vel.	Remarks
P. M. h. m.	M.	Mm.	°C.		P. ct.	g./m³.		M.p.s.	
....	12,000	....	−49.2	......	......	....	S. 14° W..	16.4	
6 10.0	12,050	160.6	−49.7	0.7	......	....	S. 14° W..	16.8	
6 16.1	12,936	140.8	−49.9	0.0	......	....	S. 5° W..	22.3	
....	13,000	....	−50.1	......	......	....	S. 7° W..	21.3	
6 18.1	13,315	132.8	−51.3	0.4	......	....	S. 16° W..	16.7	
....	14,000	....	−54.0	......	......	....	S. 22° W..	18.4	
6 24.0	14,729	107.0	−56.8	0.4	......	....	S. 29° W..	20.3	
....	15,000	....	−59.2	......	......	....	S. 23° W..	18.2	
6 29.0	15,794	90.8	−65.7	0.8	......	....	S. 4° W..	12.2	Inversion.
6 30.1	15,975	88.2	−65.3	−0.2	......	....	S. 27° E...	9.4	
....	16,000	....	−65.3	......	......	....	S. 26° E...	9.4	
6 33.0	16,611	79.4	−67.5	0.3	......	....	S. 2° W..	9.2	Inversion.
6 34.0	16,714	78.1	−66.9	−0.6	......	....	S. 34° E...	5.3	
6 35.7	16,895	76.0	−62.4	−2.5	......	....	S. 48° E...	9.1	
....	17,000	....	−62.3	......	......	....	S. 45° E...	9.6	
6 38.4	17,428	69.4	−61.8	0.0	......	....	S. 31° E...	11.4	
....	17,000	....	−61.5	......	......	....	S. 84° E...	17.9	
6 40.0	16,492	79.9	−61.2	−0.6	......	....	N. 32° E...	25.8	
....	16,000	....	−64.3	......	......	....	S. 71° E...	12.5	
6 41.7	15,838	88.6	−65.4	0.0	......	....	S. 45° E...	7.8	
6 44.1	15,208	97.8	−65.4	0.6	......	....	S. 10° W..	20.3	Inversion.
....	15,000	....	−64.0	......	......	....	S. 11° W..	19.6	
....	14,000	....	−57.9	......	......	....	S. 15° W..	16.5	
6 50.0	13,118	135.3	−52.4	0.2	......	....	S. 18° W..	13.7	
....	13,000	....	−52.2	......	......	....	....	......	
....	12,000	....	−50.2	......	......	....	....	......	
6 54.3	11,782	166.0	−49.9	0.7	......	....	....	......	
....	11,000	....	−44.5	......	......	....	....	......	
7 00.3	10,052	213.6	−37.8	0.8	......	....	....	......	
....	10,000	....	−37.5	......	......	....	....	......	
....	9,000	....	−29.4	......	......	....	....	......	
7 04.2	8,539	263.6	−25.9	0.7	......	....	....	......	
....	8,000	....	−22.4	......	......	....	....	......	
7 10.0	7,080	321.0	−16.2	0.6	......	....	....	......	
....	7,000	....	−15.7	......	......	....	....	......	
....	6,000	....	−9.4	......	......	....	....	......	
7 17.7	5,275	405.3	−5.0	0.6	......	....	....	......	
....	5,000	....	−3.2	......	......	....	....	......	
....	4,500	....	0.0	......	......	....	....	......	
....	4,000	....	3.1	......	......	....	....	......	
7 24.1	3,792	487.7	4.3	0.8	......	....	....	......	
....	3,500	....	6.6	......	......	....	....	......	
....	3,000	....	10.6	......	......	....	....	......	
....	2,500	....	14.5	......	......	....	....	......	
7 30.4	2,187	591.5	17.0	1.0	......	....	....	......	
....	2,000	....	18.9	......	......	....	....	......	
....	1,500	....	23.9	......	......	....	....	......	
7 34.1	1,208	662.5	26.7	0.9	......	....	....	......	
....	1,000	....	28.5	......	......	....	....	......	
7 35.9	849	690.0	29.8	0.4	......	....	....	......	
7 36.7	718	700.3	30.3	......	......	....	....	......	

August 7, 1913

Time	Altitude	Pressure	Temperature	Δt 100 m.	Humidity Rel.	Humidity Abs.	Wind Direction	Wind Vel.	Remarks
P. M.									
4 52.0	34	756.4	21.4	......	78	14.482	E.........	1.9	Few A. Cu., few S.
4 55.7	233	739.0	17.1	2.2	83	11.972	N. 51° W..	1.5	Inversion.
4 57.2	455	720.1	23.2	−2.7	70	14.411	S. 37° W..	2.0	
....	500	....	23.7	......	66	13.979	S. 53° W..	2.2	
4 58.9	665	703.0	26.0	−1.3	49	11.813	N. 69° W..	3.5	
5 00.7	772	694.5	28.8	−2.6	30	8.441	N. 80° W..	6.8	
....	1,000	....	29.9	......	21	6.274	N. 87° W..	7.1	
5 03.0	1,036	674.2	30.0	−0.5	20	6.007	N. 88° W..	7.2	
5 06.4	1,350	650.7	30.0	0.0	13	3.905	N. 82° W..	7.7	
5 07.8	1,440	644.1	28.8	1.3	10	2.814	N. 65° W..	4.5	
....	1,500	....	29.5	......	9	2.631	N. 69° W..	6.4	Inversion.
5 09.4	1,534	637.4	29.8	−1.1	9	2.674	N. 72° W..	7.3	
5 12.7	1,741	622.6	27.0	1.4	6	1.529	N. 43° W..	5.1	
....	2,000	....	26.9	......	6	1.521	N. 46° W..	6.5	

TABLE 4.—*Results of sounding balloon ascensions, Avalon, Cal.*—Continued

August 7, 1913—Continued

Time	Altitude	Pressure	Temperature	Δt / 100 m.	Humidity Rel.	Humidity Abs.	Wind Direction	Wind Vel.	Remarks
P. M. *h. m.*	*M.*	*Mm.*	°*C.*		*P. ct.*	*g./m.*³		*M.p.s.*	
5 17.0	2,116	596.5	26.8	0.1	6	1.512	N. 48° W..	7.1	
....	2,500	....	23.5	......	6	1.256	N. 7° E...	4.7	
5 23.0	2,551	567.5	22.8	0.9	6	1.207	N. 14° E...	4.2	
5 26.0	2,796	551.5	20.5	0.9	7	1.234	N. 8° W..	3.1	
....	3,000	....	17.8	......	9	1.353	N. 7° E...	3.5	
5 35.6	3,459	510.1	11.8	1.3	12	1.253	N. 40° E...	4.5	
....	3,500	....	11.1	......	13	1.300	N. 40° E...	4.6	5/10 A. Cu.; S.
....	4,000	....	0.7	......	21	1.065	N. 34° E...	6.4	
5 46.0	4,087	472.3	− 0.7	2.0	22	1.007	N. 33° E...	6.7	At the base of A. Cu. 5:57 p. m. Balloons disappeared.
....	4,500	....	− 7.2	......	48	1.299	N. 32° E...	7.8	
5 58.0	4,708	436.5	−10.2	1.6	61	1.292	N. 32° E...	8.4	
6 02.0	4,851	428.8	−12.7	1.7	62	1.056	....	....	
6 04.3	4,987	421.0	−12.9	0.1	80	1.338	....	....	Inversion.
....	5,000	....	−12.7	......	80	1.362	....	....	
6 05.7	5,167	411.7	−11.7	−0.7	77	1.432	....	....	
6 14.0	5,575	390.3	−14.8	0.8	69	0.979	....	....	
6 20.0	5,881	374.8	−19.1	1.4	61	0.594	....	....	
6 24.0	5,967	370.4	−19.7	0.7	49	0.450	....	....	
....	6,000	....	−19.9	......	48	0.432	....	....	
6 36.1	6,405	349.1	−24.4	0.8	34	0.221	....	....	
6 41.0	6,442	347.5	−25.2	0.5	31	0.169	....	....	

August 8, 1913

Time	Altitude	Pressure	Temperature	Δt / 100 m.	Humidity Rel.	Humidity Abs.	Wind Direction	Wind Vel.	Remarks
P. M.									
5 23.5	34	755.6	20.0	......	75	12.838	S. 32° W..	4.3	4/10 S. Cu. SSE.
5 25.1	367	726.6	17.2	0.8	80	11.608	S. 32° W..	4.3	
....	500	....	16.4	......	82	11.342	S. 62° W..	3.3	
5 26.7	786	691.5	14.4	0.7	88	10.785	N. 55° W..	0.9	Balloons in S. Cu. NW. Inversion.
....	1,000	....	19.8	......	67	11.336	N. 6° E...	1.9	
5 27.4	1,021	672.6	20.4	−2.6	64	11.213	N. 12° E...	2.0	
5 28.4	1,122	664.7	21.8	−1.4	56	10.640	N. 16° E...	0.4	
5 29.1	1,244	655.4	24.5	−2.2	49	10.859	S. 69° E...	0.2	
5 29.5	1,413	642.9	24.9	−0.2	45	10.200	S. 77° W..	1.0	
....	1,500	....	24.4	......	43	9.476	N. 82° W..	1.5	
5 30.2	1,539	633.6	24.2	0.6	42	9.151	N. 73° W..	1.8	Inversion.
5 30.7	1,711	621.3	24.3	−0.1	41	8.984	N. 45° W..	5.2	
....	2,000	....	23.1	......	39	7.983	N. 21° W..	6.0	
5 32.3	2,080	595.4	22.6	0.5	39	7.758	N. 15° W..	6.2	
....	2,500	....	19.3	......	40	6.572	N. 25° W..	3.6	
5 34.3	2,619	559.2	18.4	0.8	40	6.233	N. 28° W..	2.8	
....	3,000	....	14.5	......	41	5.055	N. 20° W..	4.1	
5 36.9	3,316	514.7	11.4	1.0	41	4.176	N. 13° W..	5.2	
....	3,500	....	9.8	......	43	3.961	N. 10° W..	4.6	
....	4,000	....	5.8	......	46	3.278	N. 2° W..	3.2	
5 40.5	4,198	462.6	4.2	0.8	48	3.079	N. 1° E...	2.7	
....	4,500	....	2.2	......	50	2.806	N. 17° W..	3.0	
5 43.4	4,981	419.9	− 0.9	0.7	53	2.387	N. 45° W..	3.4	
....	5,000	....	− 1.0	......	53	2.368	N. 45° W..	3.4	
5 46.8	5,982	369.6	− 6.5	0.6	57	1.634	S. 50° W..	3.0	
5 47.1	5,997	368.4	− 6.9	2.7	59	1.637	S. 53° W..	5.8	
....	6,000	....	− 6.8	......	58	1.623	S. 53° W..	3.0	
5 48.0	6,299	354.5	− 8.7	0.6	58	1.390	S. 75° W..	5.5	Inversion.
5 49.2	6,615	....	− 8.4	−0.1	54	1.326	S. 45° W..	3.6	Pressure pen not recording. Altitude computed from ascensional rate.
5 50.0	6,840	....	− 8.1	−0.1	52	1.308	S. 22° W..	14.6	
....	7,000	....	− 8.9	......	50	1.180	S. 11° W..	12.0	
5 50.8	7,050	....	− 9.1	0.5	49	1.137	S. 7° W..	10.7	
5 53.2	7,750	....	−13.0	0.6	46	0.763	S. 14° W..	11.5	
....	8,000	....	−14.5	......	45	0.655	S. 16° W..	12.8	

TABLE 4.—*Results of sounding balloon ascensions, Avalon, Cal.*—Continued

August 8, 1913—Continued

Time	Altitude	Pressure	Temperature	Δt / 100 m.	Humidity Rel.	Humidity Abs.	Wind Direction	Wind Vel.	Remarks
P. M. h. m.	M.	Mm.	°C.		P. ct.	g./m.³		M.p.s.	
5 54.8	8,215	....	−15.9	0.6	45	0.582	S. 18° W..	14.0	6/10 S. Cu. SSE. Balloons disappeared in St. Cu. Observations of ascension were made through this film of St. Cu. which at times obscured balloons after 5:26.5 p. m.
5 56.2	8,650	....	−19.5	0.8	45	0.422	....	....	
5 56.8	8,850	....	−20.7	0.6	45	0.375	....	....	
....	9,000	....	−21.3	......	44	0.346	....	....	
5 57.7	9,080	....	−21.7	0.4	44	0.334	....	....	
5 59.8	9,700	....	−24.3	0.4	43	0.256	....	....	
....	10,000	....	−26.1	......	43	0.215	....	....	
6 02.2	10,415	....	−28.7	0.6	42	0.162	....	....	
6 03.1	10,730	....	−29.8	0.3	42	0.145	....	....	
....	11,000	....	−31.5	......	42	0.124	....	....	
6 05.8	11,575	....	−35.0	0.6	42	0.086	....	....	
....	12,000	....	−35.8	......	41	0.077	....	....	
6 07.5	12,080	....	−36.0	0.2	41	0.076	....	....	
6 09.4	12,700	....	−37.2	0.2	40	0.065	....	....	
....	13,000	....	−38.7	......	40	0.055	....	....	
6 11.2	13,250	....	−39.8	0.5	40	0.049	....	....	
....	14,000	....	−43.4	......	40	0.033	....	....	
6 13.8	14,100	....	−43.9	0.5	40	0.031	....	....	

August 10, 1913

Time	Altitude	Pressure	Temperature	Δt / 100 m.	Humidity Rel.	Humidity Abs.	Wind Direction	Wind Vel.	Remarks
A. M.									
4 43.0	34	765.9	23.4	......	58	12.077	N. 46° E...	2.8	Cloudless.
4 45.7	435	722.6	21.3	0.5	57	10.522	N. 24° E...	1.1	Inversion.
....	500	....	21.9	......	52	9.937	N. 5° E...	1.7	
4 48.2	832	690.3	24.7	−0.9	27	6.052	N. 89° W..	4.0	
....	1,000	....	24.5	......	21	4.654	S. 88° W..	3.5	
4 49.2	1,036	674.3	24.5	0.1	20	4.432	S. 87° W..	3.4	
....	1,500	....	23.3	......	15	3.106	N. 47° W..	2.3	
4 52.4	1,549	635.7	23.2	0.3	14	2.882	N. 42° W..	2.1	
4 54.9	1,976	604.8	19.3	0.6	15	2.464	N. 47° W..	2.1	One balloon became detached; the other balloon with the meteorograph slowly descended.
....	2,000	....	19.0	......	15	2.421	N. 47° W..	2.1	
....	1,500	....	21.0	......	13	2.358	N. 43° W.	2.2	
5 00.9	1,385	647.8	21.5	0.7	13	2.428	N. 42° W..	2.2	
5 03.0	1,253	657.7	22.4	0.8	9	1.770	N. 23° W..	2.1	
....	1,000	....	24.5	......	8	1.773	N. 44° W..	1.8	
5 09.0	785	694.2	26.2	−0.3	7	1.706	N. 61° W..	1.5	
5 11.0	702	700.8	24.1	0.2	7	1.517	N. 68° W..	3.9	Inversion. Balloon disappeared behind the mountains.
5 13.1	600	709.0	24.3	−0.5	7	1.534	....	....	
....	500	....	23.7	......	16	3.389	....	....	
5 16.6	360	728.9	23.0	−1.8	27	5.495	....	....	
5 18.3	263	737.1	21.3	......	44	8.122	....	....	Inversion.

The distribution of pressure at the earth's surface changes but little in type, and that never abruptly, during the period of observation, nor does the pressure itself vary much from day to day. Figures 7 and 8 show the pressure distribution in a general way for the whole period. The positions of the centers of high and low pressure at 8 a. m. or 8 p. m., seventy-fifth meridian time, are shown by the circles, in which dates are also indicated. In the case of high pressure, these circles are connected by solid lines; in the case of low pressure, by dashed lines.

In three of the ascensions, July 24 and 27 and August 3, the balloons were followed with the theodolite beyond the altitude at which the minimum tem-

perature was recorded (see fig. 9). In another, August 2, the air movement could be observed up to 17 kilometers. On July 24 and 27 the winds were westerly, with a small south component up to the height at which the minimum temperature was found. Above this height the wind was easterly. On August 2 and 3 the winds were southerly, with a small west component up to the point of minimum temperature. Here again the winds became easterly. On July 24 the wind velocity increased as the easterly component made its appearance; on July 27 there was little change; on August 2 and 3 there was a decided decrease in velocity as the wind became easterly.

B. The Captive Balloon and Mountain Observations on and Near Mount Whitney

By W. R. Gregg

Meteorological observations, including some captive balloon ascensions, were made at Mount Whitney, Cal., from August 1 to 13, inclusive, and at Lone Pine, Cal., from August 1 to 4, inclusive. Mount Whitney is the highest peak of the Sierra Nevadas, its altitude being 4,420 meters. It lies in latitude 36° 35′ N. and longitude 118° 17′ W. On the north, south, and west it is surrounded by mountains, many of which are nearly as high as itself; its eastern slope is quite precipitous and at its foot lies Owens Valley, which is about 25 kilometers in width and extends in a north-northwest and south-southeast direction. East of this valley and running parallel to the Sierras is the Inyo Range, altitude about 3,000 meters. Lone Pine is situated about midway between these two ranges, near the northern end of Owens Lake. Its altitude is 1,137 meters and it lies in latitude 36° 35′ N. and longitude 118° 3′ W., about 25 kilometers due east from Mount Whitney. Topographically the location of Lone Pine is similar to that of Independence, Cal., which is about 25 kilometers north-northwest of it and therefore practically the same distance from Mount Whitney. Independence is in latitude 36° 48′ N., longitude 118° 12′ W., and has an altitude of 1,191 meters, or 54 meters higher than that of Lone Pine.

SURFACE OBSERVATIONS AT MOUNT WHITNEY

The instrumental equipment consisted of a Short and Mason aneroid barometer, sling psychrometer, small kite anemometer of the Robinson type, Marvin meteorograph, and Richard meteorograph. The Richard instrument recorded pressure and temperature only and the object in taking it was to obtain a surface record of these elements and also to provide a substitute in case the Marvin instrument were lost or injured. The latter recorded relative humidity in addition to pressure and temperature. In order to secure good ventilation during balloon ascensions a section of the horizontal screening tube containing the humidity and temperature elements had been cut out, thus exposing these elements directly to the air.

As soon as they were unpacked, both of these instruments were started recording and a continuous record of pressure, temperature, and relative humidity was obtained. The sheets were changed at 8 a. m. and 5 p. m., and eye readings of the aneroid barometer and psychrometer were taken at these times; also at 11 a. m. and 2 p. m., and during balloon ascensions. In addi-

tion, readings of the psychrometer were taken by Messrs. A. K. Ångström and E. H. Kennard, representing the Smithsonian Institution, during the nights when they were observing. These readings have also been used to check the meteorograph records.

The exposure of the instruments was fairly good. They were kept in an improvised shelter constructed from the boxes in which they were "packed" to the summit. The ventilation was good, but during those afternoons in which the sun shone, the air in the shelter was considerably heated. However, there were only four sunny afternoons, and furthermore, the eye readings at 2 p. m. and 5 p. m. leave but little interpolation necessary.

All of the instruments were calibrated before and after the expedition. Especial care was taken in the calibration of the aneroid barometer, tests being made to determine the correction for "lag" or "creeping" and for changes in temperature. The effect of the latter was found to be negligible.

Owing to the large scale value of the pressure elements in the meteorographs and to the effect of changes of temperature on those elements, it is impossible to obtain with much accuracy the hourly values. However, in table 5 are given the pressures observed at certain hours. The readings at 11 a. m. are uniformly higher than those at 8 a. m., 2 p. m., or 5 p. m. It is probable that the diurnal maximum occurs at about this time.

The range of pressure for the entire period is large, about 8 mm. The range for the same period at Independence is much less, about 5 mm. At both places the lowest readings were recorded on August 8 and 9, while a cyclonic disturbance was central over northern California. This low was attended by considerable cloudiness, with thunderstorms, and, at Mount Whitney, snowstorms. The greater pressure range at Mount Whitney than at Independence is accounted for by the cool weather during the passage of the low and the consequent crowding together of the isobars in the lower levels.

Tables 6, 7, and 8 contain the hourly values of temperature, relative humidity, and absolute humidity, respectively. Means have been computed for the 10 complete days, August 3 to 12, inclusive. Final conclusions may not be drawn from so short a record, but a few comparisons are of interest. The mean temperature was 0.7° C.; that in the free air at the same altitude and for the same time of year, as determined from five years' observations at Mount Weather, Va., is —2.0°. The mean temperature at Pikes Peak[1] for these 10 days in 1893 and 1894 was 2.8°. Pikes Peak has an altitude of 4,301 meters, or about 100 meters below that of Mount Whitney, and to correct for this difference in altitude about 0.6° should be subtracted from the value at Pikes Peak. The temperature at Mount Whitney was undoubtedly below normal, owing to the severe stormy weather which prevailed. However, the values at both places, compared with those at the same altitude above Mount Weather, indicate that in summer temperatures on mountains are higher than those in the free air, although difference in latitude, in this case about 2½°, should be considered. The times of maximum and minimum temperatures at Mount Whitney were 3 p. m. and 5 a. m., respectively; at Pikes Peak they were 1 p. m. and 5 a. m., respectively.

[1] Annual Reports of Chief U. S. Weather Bureau, 1893, 1894, 1895-1896, Washington.

TABLE 5.—*Pressures at Mount Whitney, Cal., August 1-13, 1913*

Date	Hours A. M. 1	2	3	4	5	6	7	8	9	10	11	12	Hours P. M. 1	2	3	4	5	6	7	8	9	10	11	12	Means
1913					*Mm.*			*Mm.*	*Mm.*	*Mm.*	*Mm.*	*Mm.*	*Mm.*	*Mm.*	*Mm.*		*Mm.*			*Mm.*	*Mm.*			*Mm.*	
Aug. 1	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......
2	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	447.0	......	......	......	......	......	......	......	......
3	......	......	......	......	......	......	......	......	446.8	447.0	447.6	447.0	447.0	446.8	446.5	......	446.0	......	......	......	446.5	......	......	......	......
4	......	......	......	......	......	......	......	446.8	......	......	......	448.1	......	446.0	......	......	445.8	......	......	446.3	......	......	......	446.0	......
5	......	......	......	......	......	......	......	445.5	......	......	446.3	......	......	446.5	......	......	445.5	......	......	......	......	......	......	......	......
6	......	......	......	......	......	......	......	444.2	......	......	445.0	......	......	444.8	......	......	444.5	......	......	444.8	......	......	......	......	......
7	......	......	......	......	......	......	......	444.8	......	......	445.3	......	......	445.3	......	......	443.5	......	......	......	......	......	......	......	......
8	......	......	......	......	......	......	......	442.7	......	......	442.5	......	......	441.4	......	......	440.7	......	......	......	......	......	......	......	......
9	......	......	......	......	......	......	......	438.7	......	......	439.2	......	......	438.9	......	......	438.9	......	......	......	......	......	......	......	......
10	......	......	......	......	......	......	......	440.4	......	......	441.2	......	......	440.4	......	......	440.2	......	......	......	......	......	......	......	......
11	......	......	......	......	......	......	......	441.4	......	......	442.0	......	......	441.7	......	......	440.4	......	......	......	......	......	......	......	......
12	......	......	......	......	......	......	......	440.9	......	......	441.7	......	......	449.9	......	......	440.4	......	......	......	......	......	......	......	......
13	......	......	......	......	438.7	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......

TABLE 6.—*Hourly Temperatures at Mount Whitney, Cal., August 1-13, 1913*

Date	Hours A. M. 1	2	3	4	5	6	7	8	9	10	11	12	Hours P. M. 1	2	3	4	5	6	7	8	9	10	11	12	Means
1913	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	
Aug. 1	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	−2.9*	......	......
2	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	1.1	−0.1	−0.6	−1.1*	−1.2	−1.4*	......
3	−1.4*	−1.9*	−2.1	−2.8	−2.9	−2.5	−1.8	0.0*	1.0	2.2*	1.7*	3.9*	2.3*	3.1*	6.1*	5.6	4.8	3.2	1.4*	0.2*	−0.2*	0.0	−0.1*	−0.4*	0.8
4	−0.6*	−1.1*	−1.1	−1.3*	−1.7*	−1.8	−1.0	−0.7*	−0.7	0.7	2.1	3.9*	4.4	4.8*	4.9	5.0	4.7*	4.5	1.9*	1.4*	1.3*	1.1*	0.6*	0.6*	1.3
5	0.6*	0.2*	0.2*	−0.1*	−0.3	−0.1	0.9	1.8*	1.7	3.0	4.2*	5.0	5.8	6.6*	7.0	5.5	4.3*	4.0	1.9*	1.8*	1.2*	1.1*	1.1*	0.6*	2.4
6	0.3*	0.6*	0.3*	0.6*	(0.6)	(1.2)	(1.6)	2.0*	2.3	3.8	5.0*	5.6	6.2	6.2*	6.4	6.6	7.8*	7.5	4.5	2.5*	2.2	2.1	2.0	2.0	3.3
7	1.9	1.8	1.7	1.6	1.6	1.6	1.7	1.9*	3.0	3.3	4.4*	5.2	5.9	6.7*	7.0	6.8	3.9*	4.4	3.8	1.9	1.4	1.5	1.5	1.4	3.2
8	1.0	0.7	0.5	0.5	0.5	0.4	0.5	1.3*	1.3	−0.2	−0.7*	0.2	0.2	−0.8*	−0.3	0.3	1.0*	1.0	0.2	−0.6	−1.1	−1.3*	−1.4	−1.4	0.1
9	−1.5	−1.5*	−1.5	−1.5	−1.5	−1.7	−1.8	−2.0*	−2.4	−0.4	−1.3*	−1.0	−0.5	−0.2*	−2.0	−1.1	−1.1*	−1.3	−2.3	−2.2	−2.2	−2.4	−2.6	−2.7	−1.6
10	−3.1	−3.4	−3.6	−3.7	−3.7	−3.2	−1.9	−0.9*	−1.0	−0.8	−0.2*	0.0	−0.7	−0.5*	−0.5	−3.0	−0.7*	−0.9	−1.2	−1.7	−2.2	−2.3	−2.3	−2.4	−1.8
11	−2.4	−2.4	−2.5	−2.7	−2.8	−2.8	−2.8	−2.6*	−2.6	−1.0	−0.1*	0.3	1.4	2.2*	2.7	2.5	2.4*	2.0	−0.6	−2.2*	−2.3*	−2.4*	−2.7*	−2.8	−1.0
12	−3.0*	−2.8	−2.6*	−2.5*	−2.5	−2.5	−1.4	−0.2*	−0.2	1.3	2.8*	3.4	4.4	5.2*	5.6	4.0	4.0*	4.0	−0.3	−1.2	−1.4	−1.6	−1.3	−1.4	0.4
13	−2.0	−2.4	−2.5	−2.6	−3.3*	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......
Means	−0.8	−1.0	−1.1	−1.2	−1.3	−1.1	−0.6	0.1	0.2	1.2	1.8	2.6	2.9	3.3	3.7	3.2	3.1	2.8	0.9	0.0	−0.3	−0.4	−0.5	−0.6	0.7
Independence means	18.6	17.8	17.2	16.3	16.5	16.7	20.4	22.9	25.2	26.9	29.2	30.6	31.2	31.4	31.4	31.3	29.9	27.7	26.1	25.3	23.7	22.0	20.4	19.8	24.1
Δt per 100 m.	0.60	0.58	0.57	0.54	0.55	0.55	0.65	0.71	0.78	0.80	0.85	0.87	0.88	0.87	0.86	0.87	0.83	0.77	0.78	0.79	0.75	0.70	0.65	0.63	0.73

* Eye readings.

TABLE 7.—*Hourly relative humidities at Mount Whitney, Cal., August 1-13, 1913*

Date	Hours																								Means
	A. M.												P. M.												
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	
1913 Aug. 1																							97*		
2																						75*		93*	
3	92*	92*	(80)	42	(50)	(60)	(70)	79*	(80)	80*	79*	74*	81*	76*	55*	60	68	71	80*	78*	85*	78	70*	72*	73
4	69*	71*	55	36*	45*	50	64	64*	68	(74)	77	77*	72	51*	60	62	62*	67	75*	66*	51*	45*	52*	51*	61
5	52*	52*	47*	50*	51	52	55	56*	48	40	32*	34	34	36*	40	45	49*	52	54*	51*	55*	43*	38*	42*	46
6	43*	40*	29*	34*	(42)	(50)	(58)	67*	64	50	57*	(58)	(59)	60*	58	57	57*	55	58	70	70	70	70	66	56
7	68	68	69	69	69	69	69	69*	68	65	63*	63	64	64*	66	68	70*	75	100	100	95	94	93	93	75
8	93	93	92	92	92	91	85	78*	80	92	93*	96	100	100*	100	100	82	82	84	85	86	86*	84	85	90
9	86	87*	87	87	88	90	94	95*	95	(92)	89*	85	90	100*	100	98	97*	99	100	100	100	99	99	98	94
10	96	93	90	85	80	85	87	86*	85	86	95*	93	92	91*	88	100	93*	94	100	100	94	99	100	100	92
11	100	100	100	96	94	94	63	50*	41	41	41*	41	41	41*	45	73	77*	72	67	63*	41*	40*	33*	31	62
12	31*	26	20*	18*	18	30	40	50*	48	46	43*	43	43	43*	47	56	62*	50	72	76	54	54	15	15	42
13	15	19	19	19	23*																				
Means	73	72	67	61	63	67	68	69	68	67	67	66	68	66	66	72	72	72	79	79	73	71	65	66	69

TABLE 8.—*Absolute humidities in grams per cubic meter at Mount Whitney, Cal., August 1-13, 1913*

Date.	Hours																								Means
	A. M.												P. M.												
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	
1913 Aug. 1																							3.7*		
2																						3.3*		4.0*	
3	4.0*	3.8*	(3.3)	1.6	(1.9)	(2.4)	(2.9)	3.8*	(4.1)	4.5*	4.3*	4.7*	4.6*	4.5*	4.0*	4.2	4.5	4.3	4.3*	3.8*	4.0*	3.8	3.4*	3.4*	3.8
4	3.2*	3.1*	2.4	1.6*	1.9*	2.1	2.9	2.9*	3.1	(3.8)	4.3	4.8*	4.7	3.4*	4.0	4.2	4.1*	4.4	4.1*	3.5*	2.7*	2.3*	2.6*	2.6*	3.3
5	2.6*	2.5*	2.3*	2.4*	2.4	2.5	2.8	3.1*	2.6	2.4	2.1*	2.3	2.4	2.7*	3.1	3.1	3.2*	3.3	3.0*	2.8*	2.9*	2.2*	2.0*	2.1*	2.6
6	2.1*	2.0*	1.4*	1.7*	(2.1)	(2.6)	(3.1)	3.7*	3.6*	3.1	3.9*	(4.1)	(4.3)	4.4*	4.3	4.3	4.6*	4.4	3.8	4.0*	3.9	3.9	3.9	3.7	3.5
7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.8*	4.0	3.9	4.1*	4.3	4.6	4.8*	5.1	5.2	4.4*	4.9	6.2	5.5	5.1	5.0	5.0	4.9	4.4
8	4.8	4.7	4.6	4.6	4.6	4.5	4.3	4.1*	4.2	4.4	4.3*	4.7	4.9	4.5*	4.7	4.9	4.2*	4.2	4.1	3.9	3.8	3.8*	3.6	3.7	4.3
9	3.7	3.7	3.7	3.7	3.8	3.8	3.9	3.9*	3.8	(4.3)	3.9*	3.8	4.2	4.8*	4.1	4.3	4.3*	4.3	4.0	4.1	4.1	4.0	3.9	3.8	4.0
10	3.6	3.4	3.3	3.1	2.9	3.2	3.6	3.9*	3.8	3.9	4.5*	4.5	4.2	4.2*	4.1	3.8	4.3*	4.2	4.4	4.2	3.8	4.0	4.0	4.0	3.9
11	4.0	4.0	4.0	3.7	3.6	3.6	2.4	2.0*	1.6	1.9	2.0*	2.0	2.2	2.3*	2.6	4.2	4.4*	4.0	3.1	2.6*	1.7*	1.6*	1.3*	1.2	2.8
12	1.2*	1.0	0.8*	0.7*	0.7	1.2	1.7	2.4*	2.3	2.4	2.5*	2.6	2.8	2.9*	3.3	3.5	3.9*	3.2	3.4	3.3	2.3	2.3	0.7	0.6	2.2
13	0.6	0.8	0.8	0.7	0.9																				
Means	3.3	3.2	3.0	2.7	2.8	3.0	3.1	3.4	3.3	3.5	3.6	3.8	3.9	3.8	3.9	4.2	4.2	4.1	4.0	3.8	3.4	3.3	3.0	3.0	3.5

* Indicates eye readings. ( ) inclose estimated values. All others from meteorograph records.

Figure 10 shows mean hourly temperatures at Mount Whitney and Independence and for the same period during 1893 and 1894 at Pikes Peak. The range at the latter appears to be somewhat smaller than at Mount Whitney, and this may be due to the fact that conditions at Pikes Peak are more nearly like those of the free air, owing to its isolation and the consequent freer circulation. The curve for Independence shows the large diurnal range characteristic of valley stations. Beneath the mean temperatures for Mount Whitney in table 6 are given the means for the same period at Independence and the differences in temperature change per 100 meters altitude between

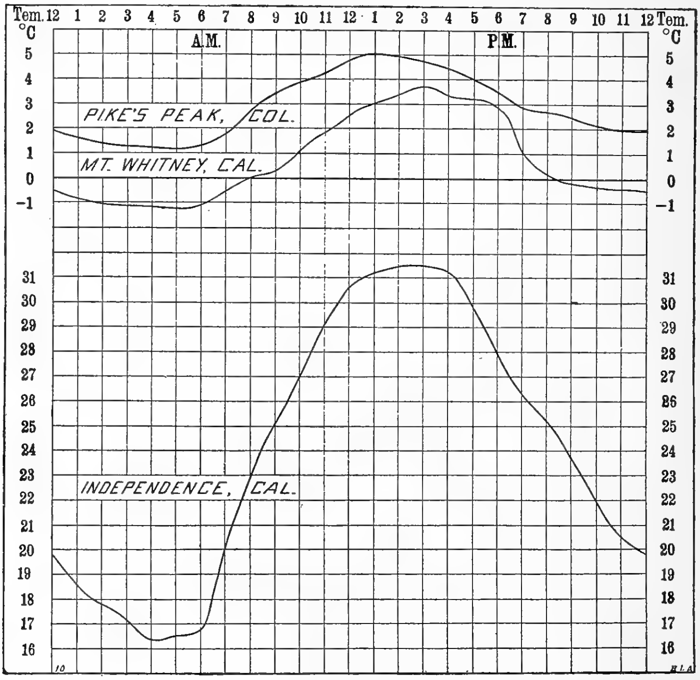

Fig. 10.—Mean hourly temperatures at Mount Whitney and Independence, Cal., August 3 to 12, incl., 1913, and at Pikes Peak, Col., August 3 to 12, incl., 1893 and 1894.

the two places. The temperature change with altitude during the night hours is somewhat misleading, owing to a marked inversion of temperature between the surface of the valley and about 200 meters above it, as will be pointed out in discussing the Lone Pine observations. The hourly differences between Independence and Mount Whitney during the daytime are large, averaging about 0.85. The mean for the 24 hours is 0.73.

The relative humidity, table 7, was probably higher than normal for this season of the year, owing to the unusually stormy weather and the presence of snow on the ground. The mean was 69 per cent, the mean maximum 79 per cent at 7 to 8 p. m., and the mean minimum 61 per cent at 4 a. m. During the severe storm of August 8, 9, and 10, 100 per cent was frequently recorded. The absolute minimum was 15 per cent at midnight of the 12th.

TABLE 9.—*Wind velocities, in meters per second, at Mount Whitney, Cal., during August, 1913*

Date	A. M. 1	2	3	4	5	6	7	8	9	10	11	12	P. M. 1	2	3	4	5	6	7	8	9	10	11	12
1913 Aug. 1	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
2	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	←		2.6			
3	←				2.6					→	1.3	1.8	1.8	1.3	1.3	1.8		*	2.1	→	3.6	←	3.8	
4	←				3.8				*	3.8		→	2.2		*	1.5		*	1.3	→	2.5			→
5	←				1.8				*	1.5		*	2.8		*	2.1		*			3.4			
6					3.4				*	0.9		*	1.9		*	1.2		*			3.6			
7					3.6				*	3.7		*	5.5		*	3.6		*			3.0			
8					3.0				*	2.4		*	3.1		*	1.5		*			2.0			
9					2.0				*	2.8		*	2.4		*	3.7		*			1.4			
10					1.4				*	1.4		*	2.1		*	2.8		*			3.5			
11					3.5				*	4.1		*	3.7		*	3.7		*			3.7			
12					3.7				*	4.9		*	5.7		*	4.6		*			5.6			
13					5.6	→	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....

Mean velocity for entire period, 3 m. p. s.
NOTE.—Anemometer read at the times indicated by *; figures are mean velocities between readings.

TABLE 10.—*State of weather at Mount Whitney, Cal., during August, 1913*

Date.	A. M. 1	2	3	4	5	6	7	8	9	10	11	12	P. M. 1	2	3	4	5	6	7	8	9	10	11	12	Remarks
1913 Aug. 1	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	←			Cloudy.		→	Clear	←	*, ☈ until 10 p. m.
2												Cloudy.					→	Pt. cldy.		Clear.					*, ☈ in p. m.
3	→	Pt. cldy.		Clear.		Pt. cldy.		←				Cloudy.		→	←	Pt. cldy.		→	←	Clear.					≡ 2a, Cu. from SE.
4												Clear.				→	Pt. cldy.		←	Clear.					Cu. from S. ⚡ in NE in evening.
5												Clear.													Cu. & Cu. N. from S.; ⚡ in NE. in evening.
6					Clear.							→	←			Pt. cldy.		→	←	Clear.					Cu.&Cu. N. from S.; ☈ near by in p.m
7					Clear.				→	←		Pt. cldy.			→	←				Cloudy.					☈ near by; * 5:30 p.-12 p.
8												Cloudy.								→	Pt. cldy.		Clear.		*²—4:30 p.
9	Cl'r.	Pt. cldy.		←								Cloudy.								→	←	Pt. cldy.			Snow squalls. *² 6 p.; ≡².
10	Pt. cldy.		←	Clear.		→	←	Pt. cldy.		→	←	Cloudy.												→	*² 9:30 a.-9 p.
11	←	Pt. cldy.		→	←							Clear.													Cu. from east and southeast.
12												Clear.												→	Cu. from south.
13	←	Pt. cldy.				→	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	Ci. and S. Cu. from south.

For the reasons given above, the absolute humidity, table 8, was also probably higher than normal. The mean was 3.5 grams per cubic meter, the mean maximum 4.2 at 4 to 5 p. m., and the mean minimum 2.7 at 4 a. m. The absolute maximum was 6.2 at 7 p. m. of the 7th and the absolute minimum 0.6 at midnight of the 12th.

Table 9 gives roughly the average wind velocities. Dial readings of the anemometer were made at the times indicated by stars. The figures between these stars represent average velocities for the intervals between readings. The mean for the entire period was 3.0 m. p. s. That at Pikes Peak for the same time of year was 6.0 m. p. s. This difference may be due partly to the fact that Pikes Peak stands out in the open, whereas Mount Whitney is surrounded by peaks nearly as high as itself, and also to the greater proximity of Pikes Peak to the cyclonic storm paths of the United States. The prevailing wind direction was southeast, but directions ranging between south and northeast were frequently observed, and a southwesterly wind prevailed during the blizzard of August 9.

In table 10 may be found the state of the weather for the period, together with notes on storms, kinds of clouds, and miscellaneous phenomena.

FREE-AIR OBSERVATIONS AT MOUNT WHITNEY, CAL.

The place from which balloon ascensions were made was about 60 meters to the northwest of the summit of Mount Whitney and about 10 meters below it. This was the only spot on the mountain that was fairly level and free from jagged surface rocks. While the balloon was being filled with gas it rested on a large piece of canvas to protect it from rocks and snow. The gas, compressed in steel cylinders, was furnished by the Signal Corps of the United States Army. A hand reel was used for reeling the wire in and out. Readings of the psychrometer, aneroid barometer, and anemometer were made with the aid of a pocket electric flash lamp.

Ascensions were made on only three nights, August 3, 4, and 5, and were begun immediately after sundown. On all other nights the weather was either too windy or too stormy. The balloon was allowed to take as great an altitude as possible and was then kept out until the wind aloft had increased to such an extent that it was necessary to reel in.

Table 11 contains the tabulated data for the three records obtained, and in figures 11 and 12 are plotted the temperature and absolute humidity gradients, respectively; the slight changes with time at the higher levels in each ascension are not plotted; only the ascent and descent proper. On August 3 and 4 these elements diminished with time by nearly the same amounts at all upper levels as at the surface. There was but little wind during these nights. On August 5, however, there was a fairly high northeast wind aloft and the temperature and humidity changed very little with time. The change with altitude in temperature was greater and in absolute humidity less than on the other nights.

TABLE II.—*Results of captive balloon ascensions at Mount Whitney, Cal., August 3-5, 1913*

Date and hour	Surface				At different heights above sea					
	Pressure	Temperature	Rel. hum.	Wind direction	Height	Pressure	Temperature	Humidity Rel.	Humidity Abs.	Wind dir.
Aug. 3, 1913:	*Mm.*	°*C.*	*P. ct.*		*M.*	*Mm.*	°*C.*	*P. ct.*	*g./cu.m.*	
7:13 p. m.	446.2	0.6	80	S.	4,410	446.2	0.6	80	4.0	S.
7:18 p. m.	446.2	0.3	81	S.	4,533	439.3	−0.2	65	3.1	ESE.
7:25 p. m.	446.2	0.1	80	S.	4,631	434.0	−0.9	65	2.9	ESE.
7:35 p. m.	446.3	0.3	78	Calm.	4,689	430.9	−1.5	......	....	E.
7:45 p. m.	446.3	0.2	78	Calm.	4,801	424.9	−2.3	......	....	E.
7:58 p. m.	446.3	0.3	75	E.	4,683	431.2	−0.8	29	1.3	E.
8:06 p. m.	446.3	0.3	73	E.	4,801	424.9	−1.5	18	0.8	E.
8:10 p. m.	446.3	0.3	74	E.	4,744	427.9	−1.3	16	0.7	E.
8:15 p. m.	446.4	0.2	75	E.	4,802	424.9	−2.3	13	0.5	E.
8:18 p. m.	446.4	0.2	76	E.	4,664	432.4	−2.0	26	1.1	E.
8:31 p. m.	446.4	0.1	78	ENE.	4,579	437.0	−1.5	67	2.9	ENE.
8:41 p. m.	446.4	0.0	79	ENE.	4,509	440.9	−0.7	68	3.1	ENE.
8:51 p. m.	446.5	−0.2	85	ENE.	4,410	446.5	−0.2	85	4.0	ENE.
Aug. 4, 1913:										
6:45 p. m.	446.1	2.3	77	Calm.	4,410	446.1	2.3	77	4.4	Calm.
6:49 p. m.	446.2	2.2	78	Calm.	4,627	434.3	1.4	......	....	Calm.
6:56 p. m.	446.2	2.0	76	Calm.	4,852	422.3	−0.9	64	2.9	Calm.
7:04 p. m.	446.2	1.8	74	Calm.	5,104	409.1	−2.2	37	1.5	Calm.
7:12 p. m.	446.2	1.6	72	Calm.	5,359	396.1	−4.8	34	1.1	SSW.
7:22 p. m.	446.2	1.6	71	Calm.	5,230	402.6	−4.4	33	1.1	S.
7:45 p. m.	446.3	1.6	70	Calm.	5,316	398.3	−5.6	24	0.7	WSW.
7:56 p. m.	446.3	1.3	67	Calm.	5,216	403.3	−4.9	23	0.8	WSW.
8:25 p. m.	446.3	1.1	60	E.	5,258	401.2	−4.4	19	0.6	SW.
8:55 p. m.	446.2	1.1	55	Calm.	5,201	404.0	−3.6	12	0.4	SSW.
9:13 p. m.	446.2	1.1	50	Calm.	5,229	402.6	−3.6	12	0.4	SSW.
9:39 p. m.	446.2	0.9	46	Calm.	5,299	399.0	−5.6	12	0.4	S.
10:00 p. m.	446.2	0.8	45	Calm.	5,198	404.0	−4.3	12	0.4	S.
11:45 p. m.	446.0	0.6	51	E.	4,634	433.6	−1.9	10	0.4	E.
11:50 p. m.	446.0	0.6	51	E.	4,509	440.5	−0.7	23	1.1	E.
12:00 mdt.	446.0	0.6	51	E.	4,410	446.0	0.6	51	2.6	E.
Aug. 5, 1913:										
6:38 p. m.	446.0	2.8	51	Calm.	4,410	446.0	2.8	51	3.0	Calm.
6:54 p. m.	446.1	2.5	52	Calm.	4,625	434.3	0.8	54	2.8	SW.
7:30 p. m.	446.2	1.8	50	Calm.	4,810	424.4	−1.4	54	2.3	NE.
7:37 p. m.	446.3	1.8	45	Calm.	4,995	414.7	−2.8	54	2.1	NE.
7:52 p. m.	446.4	1.9	47	Calm.	4,997	414.7	−3.5	54	2.0	NE.
8:05 p. m.	446.4	1.8	53	Calm.	4,898	419.9	−2.7	54	2.1	NE.
8:17 p. m.	446.5	1.7	57	Calm.	4,999	414.7	−3.4	54	2.0	NE.
8:42 p. m.	446.6	1.3	55	Calm.	4,861	422.1	−1.8	54	2.3	NE.
8:56 p. m.	446.7	1.2	55	Calm.	4,736	428.9	−0.3	53	2.5	NE.
9:05 p. m.	446.7	1.3	55	NE.	4,820	424.4	−1.1	53	2.4	NE.
9:20 p. m.	446.6	1.3	51	NE.	4,734	428.9	−0.3	51	2.4	NE.
9:44 p. m.	446.5	1.2	46	NE.	4,604	435.8	1.0	48	2.5	NE.
11:00 p. m.	446.1	1.1	38	NE.	4,410	446.1	1.1	38	2.0	NE.

Aug. 3, 1913.—One captive balloon was used; capacity, 28.6 cu. m.
Few Cu., from the east, prevailed throughout the ascension.

Aug. 4, 1913.—One captive balloon was used; capacity, 28.6 cu. m.; lifting force at beginning of ascension, 5.4 kg.
Few Cu., from the south, at 7 p. m. Cloudless by 9 p. m. Lightning was seen over or near Death Valley. There was considerable electricity on the wire.

Aug. 5, 1913.—One captive balloon was used; capacity, 28.6 cu. m.
Few Cu., direction unknown, in early evening. Cloudless after 8.50 p. m. Lightning was seen on the eastern horizon, near Death Valley.

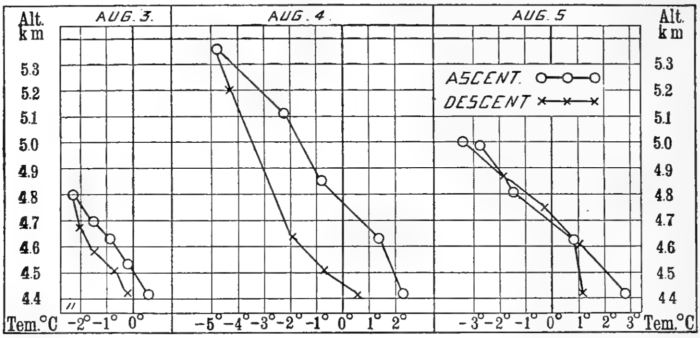

FIG. 11.—Temperature gradients (°C.), above Mount Whitney, Cal., August 3, 4, and 5, 1913.

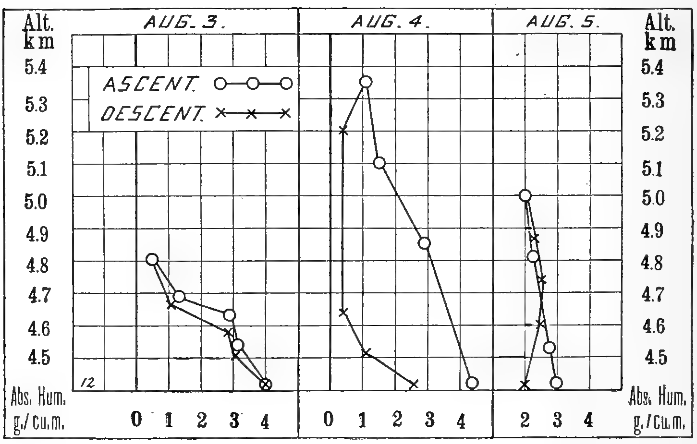

FIG. 12.—Absolute humidity gradients, grams per cubic meter, above Mount Whitney, Cal., August 3, 4, and 5, 1913.

TABLE 12.—*Temperature differences at 100-meter intervals above Mount Whitney, Cal., August 3, 4, 5, 1913*

Observations	Altitudes (meters)								
	100	200	300	400	500	600	700	800	900
Aug. 3, 1913:									
Ascent	0.6	0.8	0.9	0.6	....	....	....	....	....
Descent	0.5	1.0	0.4	0.2	....	....	....	....	....
Aug. 4, 1913:									
Ascent	0.4	0.4	0.9	1.0	0.7	0.5	0.6	1.0	1.0
Descent	1.3	1.0	0.5	0.4	0.5	0.4	0.4	0.4	0.4
Aug. 5, 1913:									
Ascent	0.9	1.0	1.1	1.2	0.8	0.8	....	....	....
Descent	0.1	0.1	0.9	1.2	1.1	1.2	....	....	....
Means	0.63	0.72	0.77	0.77	0.78	0.72	0.50	0.70	0.70

Table 12 contains the temperature differences at 100-meter intervals above the surface, as observed in all three ascensions. The mean gradient is 0.70 and is fairly constant at all altitudes up to 900 meters.

FREE-AIR OBSERVATIONS AT LONE PINE, CAL.

The balloon ascensions were carried out by Mr. P. R. Hathaway from a place about 1 kilometer north of Lone Pine. The instrumental and other equipment was similar to that used at Mount Whitney. Owing to leakage of a large number of gas tubes, only four ascensions were possible. These were made on August 1, 2, 3, and 4, and were begun shortly after sundown. Surface conditions for making ascensions at this time of day were usually excellent.

TABLE 13.—*Results of captive balloon observations at Lone Pine, Cal., August 1-4, 1913*

Date and hour	Surface				At different heights above sea					
	Pressure	Temperature	Rel. hum.	Wind direction	Height	Pressure	Temperature	Humidity Rel.	Humidity Abs.	Wind dir.
Aug. 1. 1913:	*Mm.*	°*C.*	*P. ct.*		*M.*	*Mm.*	°*C.*	*P. ct.*	*g./cu.m.*	
9:18 p. m.	660.3	16.7	79	Calm.	1,137	660.3	16.7	79	11.1	Calm.
9:30 p. m.	660.4	16.7	79	Calm.	1,190	656.3	21.1	50	9.1	W.
9:37 p. m.	660.5	16.8	78	Calm.	1,296	648.5	22.2	37	7.2	W.
9:44 p. m.	660.6	17.2	77	Calm.	1,297	648.5	21.4	37	6.9	W.
10:10 p. m.	660.8	18.3	72	W.	1,311	647.7	23.0	28	5.7	W.
10:15 p. m.	660.8	16.7	80	Calm.	1,470	636.0	23.1	24	4.9	W.
10:43 p. m.	661.0	16.7	78	S.	1,204	655.8	22.3	46	9.0	S.
10:48 p. m.	661.1	16.7	78	S.	1,137	661.1	16.7	78	11.0	S.
Aug. 2, 1913:										
7:38 p. m.	658.3	23.9	46	NNW.	1,137	658.3	23.9	46	9.9	NNW.
7:41 p. m.	658.5	24.2	45	NNW.	1,253	649.9	27.2	30	7.7	N.
7:47 p. m.	658.8	22.6	48	NNW.	1,355	642.8	27.1	17	4.4	N.
8:01 p. m.	659.3	19.4	64	S.	1,958	600.4	23.0	17	3.5	Calm.
8:48 p. m.	660.0	19.7	57	Calm.	2,273	579.8	19.2	23	3.8	SE.
9:30 p. m.	660.9	18.6	66	Calm.	1,811	612.1	22.7	20	4.0	SE.
10:48 p. m.	662.6	17.5	69	S.	1,724	618.9	22.9	20	4.0	SW.
10:56 p. m.	662.8	18.0	64	S.	1,728	619.7	21.9	21	4.0	SW.
11:05 p. m.	662.9	16.4	77	S.	1,432	641.0	24.3	23	5.0	SE.
11:13 p. m.	662.9	16.7	75	S.	1,316	649.4	25.6	21	5.0	E.
11:19 p. m.	662.9	17.0	70	W.	1,234	655.5	25.5	21	4.9	E.
11:25 p. m.	662.9	17.2	70	W.	1,137	662.9	17.2	70	10.2	W.
Aug. 3, 1913:										
7:17 p. m.	661.8	21.7	54	Calm.	1,137	661.8	21.7	54	10.2	Calm.
7:21 p. m.	661.9	21.7	54	Calm.	1,296	650.0	28.4	26	7.2	SSE.
9:25 p. m.	664.5	22.9	37	SSW.	1,137	664.5	22.9	37	7.5	SSW.
Aug. 4, 1913:										
7:19 p. m.	656.9	19.9	58	Calm.	1,137	656.9	19.9	58	9.9	Calm.
7:22 p. m.	657.0	19.8	57	Calm.	1,309	644.4	20.6	......	....	SE.
7:34 p. m.	657.4	21.0	43	Calm.	2,367	572.2	23.2	......	....	SE.
7:56 p. m.	658.2	22.2	39	S.	2,106	589.9	24.4	......	....	SSE.
8:02 p. m.	658.3	22.7	38	S.	1,629	622.7	28.9	......	....	SSE.
8:05 p. m.	658.3	23.0	38	S.	1,459	634.9	30.6	......	....	SSE.
8:55 p. m.	658.2	26.4	27	S.	1,137	658.2	26.4	27	6.7	S.

Aug. 1, 1913.—One captive balloon was used; capacity, 28.6 cu. m. Cu. Nb., from the west, decreased from 5/10 to a few. Light rain fell for about two minutes at 9.35 p. m.

Aug. 2, 1913.—One captive balloon was used; capacity, 31.1 cu. m. St. Cu., from the south, decreased from 6/10 to a few.

Aug. 3, 1913.—One captive balloon was used; capacity, 31.1 cu. m. 1/10 Cu., direction unknown, disappeared before the end of the ascension.

Aug. 4, 1913.—One captive balloon was used; capacity, 31.1 cu. m. The sky was cloudless.

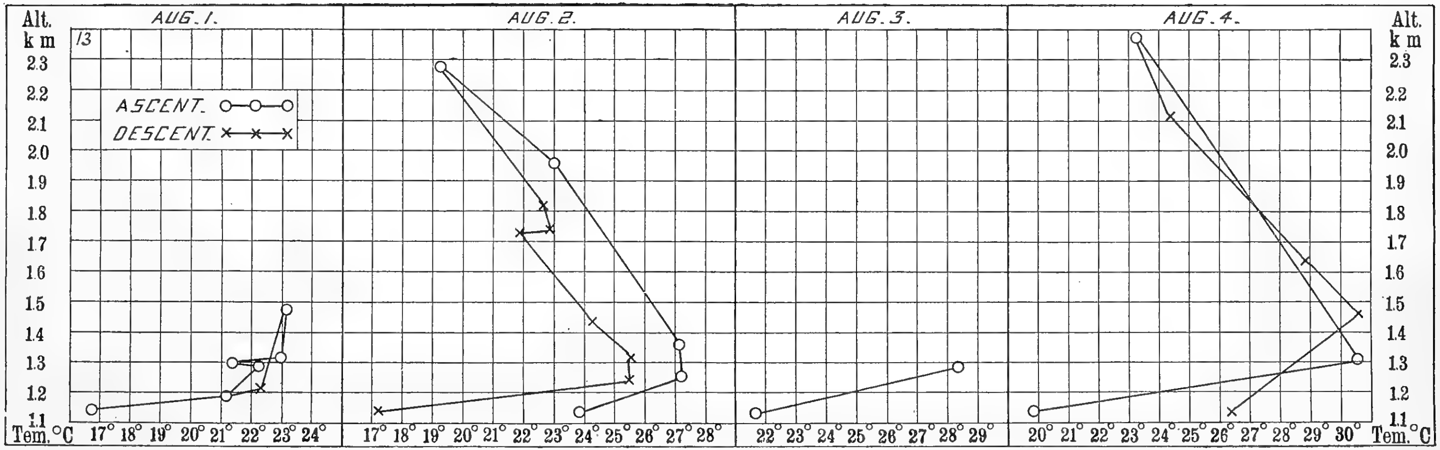

FIG. 13.—Temperature gradients (°C.), above Lone Pine, Cal., August 1, 2, 3, and 4, 1913.

The records obtained in the balloon ascensions are given in tabular form in table 13. Figures 13 and 14 show the temperature and absolute humidity gradients, respectively. There was always a marked inversion of temperature between the surface and 200 meters above it, amounting on the average to 6° C. (See table 14.) From 200 to 300 meters there was practically no change, but above 300 meters the temperature decreased with altitude at a

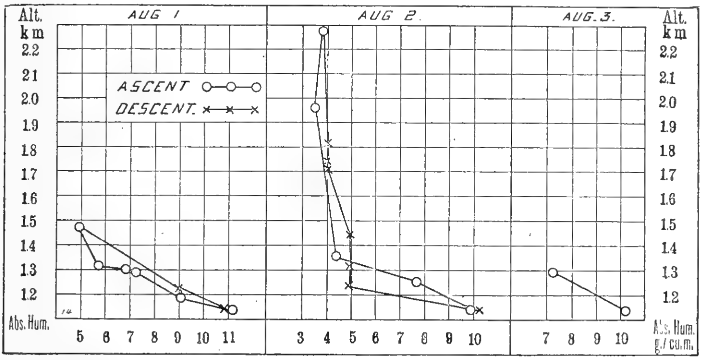

FIG. 14.—Absolute humidity gradients, grams per cubic meter, above Lone Pine, Cal., August 1, 2, and 3, 1914.

TABLE 14.—*Temperature differences at 100-meter intervals above Lone Pine, Cal., August 1-4, 1913*

Observations	Altitude (meters) 100	200	300	400	500	600	700	800	900	1,000	1,100	1,200
Aug. 1, 1913:												
Ascent	−4.8	−1.5	−0.1	......	......	......	......	......	......	......	......	......
Descent	−5.7	−0.3	−0.3	......	......	......	......	......	......	......	......	......
Aug. 2, 1913:												
Ascent	−2.7	−0.5	0.5	0.7	0.7	0.7	0.7	0.6	1.1	1.2	1.2	......
Descent	−8.3	0.1	1.1	0.8	0.8	−0.2	0.4	0.7	0.8	0.7	0.8	......
Aug. 3, 1913:												
Ascent	−4.2	......	......	......	......	......	......	......	......	......	......	......
Aug. 4, 1913:												
Ascent	−6.2	−4.3	0.7	0.7	0.7	0.7	0.6	0.7	0.7	0.7	0.7	0.7
Descent	−1.3	−1.3	−1.3	0.5	1.0	0.9	1.0	0.9	0.9	0.8	0.5	0.5
Means	−4.74	−1.30	0.10	0.68	0.80	0.52	0.68	0.72	0.88	0.85	0.80	0.60

fairly uniform rate, the mean difference per 100 meters being 0.73. On August 2 there was about equal cooling with time at all levels; on the 4th the temperature changed but little at upper levels and increased somewhat at the surface.

The absolute humidity (fig. 14) diminished rapidly from the surface to the altitude at which the highest temperature was recorded. Above this, on August 2, the only night in which a record of humidity at higher levels was obtained, it diminished slowly.

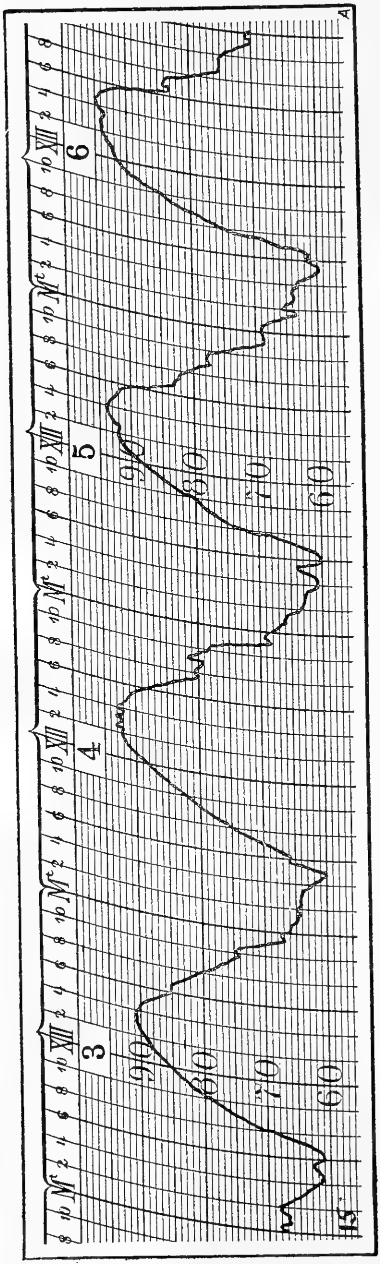

FIG. 15.—Thermograph record (°F.), at Independence, Cal., August 3-6, incl., 1914, showing fluctuations in temperature during night-time.

During the day there was a moderate breeze from the north blowing down the valley. This became very light toward evening, and at about the same time the temperature began to fluctuate, sudden changes of 2° to 5° C. occurring frequently between 6 p. m. and the time of minimum temperature. These fluctuations are well shown in the thermograph records at Independence, Cal. (fig. 15), and in table 15, which contains observed temperatures and humidities at Lone Pine, Cal. These observations have been referred to by Dr. Wm. R. Blair in his discussion of mountain and valley temperatures (Bulletin Mount Weather Observatory, Washington, 1914, **6**: 122) and are in accord with the conclusion there reached that "there is not a stream of cool air past the slope station, but a direct convective interchange between the cool air on the slope and the free air over the valley at the same or slightly lower levels." In general, as shown in table 15, the lower temperatures were accompanied by the higher absolute humidities.

TABLE 15.—*Fluctuations in surface temperature and humidity at Lone Pine, Cal., August 2 and 3, 1913*

Date	Time	Temperature	Relative humidity	Absolute humidity
1913	*P. m.*	*°C.*	*Per cent.*	*g./cu. m.*
Aug. 2	7:48	22.2	48	9.3
	7:51	20.6	56	9.9
	8:01	*19.4*	*64*	*10.6*
	8.45	20.0	56	9.6
	9:10	*16.7*	*75*	*10.6*
	9:21	18.7	64	10.2
	10:01	*16.7*	*75*	*10.6*
	11:00	18.3	62	9.6
	11:05	*16.4*	*77*	*10.7*
	11:48	18.9	60	9.6
Aug. 3	6:50	25.1	40	9.2
	7:40	*21.1*	*56*	*10.2*
	7:50	*19.4*	*56*	*9.3*
	8:05	20.8	45	8.1
	8:37	*19.4*	*52*	*8.6*
	9:09	21.1	42	7.7
	9:33	23.9	34	7.3
	9:43	*21.8*	*47*	*8.9*

Between 8 and 10.30 p. m. it was necessary to bring the balloon down because of southerly or southeasterly winds aloft. These winds gradually extended toward the surface and were warm and dry (table 13). The mixing of the upper southerly and the lower northerly currents seems to account for the variations in surface temperature and humidity already referred to.

The fact that the upper southerly wind is warm and dry suggests the probability that it originates over the Mohave Desert, which is about 150 kilometers south of Lone Pine. The heating and consequent rising of air over the desert in the daytime, which gives rise to the southerly current aloft, at the same time causes the surface northerly current down the valley.

APPENDIX II

SUMMARY OF SPECTROBOLOMETRIC WORK ON MOUNT WILSON DURING MR. ÅNGSTRÖM'S INVESTIGATIONS

By C. G. Abbot

Table 16, similar in form to tables 35 and 36 of Vol. III of the Annals of the Astrophysical Observatory of the Smithsonian Institution, contains a summary of all Mount Wilson spectrobolometric observations obtained by Mr. Aldrich, with accompanying measurements and reductions, for days in which Mr. Ångström obtained observations in California in 1913. The final column is of interest in connection with the pyrheliometric observations on Mount Whitney, given in Appendix III. The third column contains spectroscopic determinations by Mr. Fowle of the total depth of precipitable water existing as vapor above the observing station at Mount Wilson (latitude 34° 12′ 55″ N., longitude 118° 03′ 34″ W., elevation 1,727 meters or 5,665 feet). The letters given under "grade" have the following meanings: *vp*, very poor; *p*, poor; *g*, good; *vg*, very good; *e*, excellent. All observations were made between 6 and 10 o'clock in the morning except those of August 8, which were made between 2 and 6 o'clock in the afternoon. For a discussion of the methods and apparatus used the reader is referred to Vol. III of the Annals, cited above.

TABLE 16

Date	Pressure, water vapor	Precipitable water	Pyrheliometry			Bolometry Atmospheric transmission for different wave lengths											Solar constant (preliminary)	Ratio	True atmospheric transmission	True solar constant corrected for zero water vapor
			Grade	Apparent atmospheric transmission	Apparent solar constant	Grade	μ 0.35	μ 0.40	μ 0.45	μ 0.50	μ 0.60	μ 0.70	μ 0.80	μ 1.00	μ 1.20	μ 1.60				
1913	*cm.*	*cm.*		a	A_0												E_0	$\frac{E'_0}{A_0}$	$\frac{A_0 a}{E'_0}$	E'_0
July 23....	0.68	1.17	*g*	.865	1.711	*vg*—	.656	.730	.768	.786	.845	.917	.931	.956	.951	.973	1.914	1.131	.765	1.935
24....	0.73	1.15	*g*+	.869	1.685	*vg*+	.540	.692	.765	.814	.850	.930	.932	.956	.967	.989	1.890	1.135	.766	1.911
Aug. 3....	0.73	1.39	*vg*+	.861	1.716	*e*	.614	.712	.760	.808	.855	.908	.928	.948	.948	.977	1.903	1.124	.766	1.928
4....	0.55	1.19	*vg*	.867	1.646	*e*—	.621	.723	.783	.811	.853	.922	.951	.968	.969	.957	1.895	1.164	.745	1.916
5....	0.25	0.54	*g*+	.881	1.759	*e*	.621	.707	.766	.825	.843	.915	.936	.959	.964	.984	1.948	1.107	.796	1.958
P. M. 8....	1.04	2.06	*vp*	.762	1.769	*p*	.432	.541	.610	.676	.721	.816	.864	.916	.900	.916	2.016	1.162	.655	2.056
9....	0.69	1.34	*e*	.813	1.717	*e*—	.538	.608	.665	.728	.798	.854	.890	.921	.930	.968	1.932	1.140	.713	1.957
10....	0.68	1.30	*g*	.853	1.681	*vg*—	.552	.680	.737	.782	.824	.892	.919	.948	.947	.980	1.929	1.163	.734	1.954
11....	0.65	1.15	*vg*	.877	1.692	*vg*—	.562	.710	.774	.829	.863	.919	.931	.949	.965	.998	1.900	1.137	.772	1.921
12....	0.54	0.59	*e*—	.885	1.751	*vg*	.597	.750	.790	.816	.871	.930	.952	.974	.975	.966	1.928	1.108	.798	1.940
14....	0.32	0.65	*vg*	.883	1.757	*e*—	.670	.718	.781	.834	.861	.914	.942	.968	.946	.959	1.942	1.113	.793	1.955

APPENDIX III[1]

SOME PYRHELIOMETRIC OBSERVATIONS ON MOUNT WHITNEY

By A. K. Ångström and E. H. Kennard

In the summer of 1913 an expedition supported by a grant from the Smithsonian Institution proceeded to California in order to study the nocturnal radiation under different atmospheric conditions. In connection with these investigations we had an opportunity to measure the intensity of the solar radiation during seven clear days on the summit of Mount Whitney (4,420 m.). These measurements were made for different air masses and include observations of the total radiation and of the radiation in a special part of the spectrum, selected by means of an absorbing screen, as had been proposed by K. Ångström.[2] Our paper will present the results of the observations and a computation from them of the solar constant.

INSTRUMENTS

The observations were made with Ångström's pyrheliometer No. 158. With this instrument the energy of the radiation falling upon the exposed strip is given in calories per square centimeter per minute by the relation $I = kC^2$, where C is the compensating current sent through the shadowed strip, and k is a constant which was determined for this instrument at the solar observatory of the Physical Institute in Upsala and found to be 13.58.[3] The compensating current was furnished by four dry cells, which proved entirely suited to the purpose. It was measured by a Siemens and Halske milliammeter. For further details of the instrument and the method of using it, we refer to the original paper.[4]

The absorbing screen, used in order to study a limited part of the spectrum, was composed of a water cell, in which the water layer had a thickness of 1 cm., and a colored glass plate, Schott and Genossen, 436^{III}, the thickness of which was 2.53 mm. The transmission of the combination for different wave lengths as previously determined at Upsala by Mr. A. K. Ångström is given in figure 16. The maximum of transmission occurs at wave length 0.526 μ, and 85 per cent of the transmitted light is included between 0.484 μ and 0.570 μ.

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[1] Reprinted by permission from the Astrophysical Journal, Vol. 39, No. 4, pp. 350-360.

[2] Nova Acta Reg. Soc., Sc. Upsal., Ser. IV, **1**, No. 7.

[3] A comparison made at the Smithsonian Institution in Washington showed that the readings of this instrument are 4.57 per cent lower than the Smithsonian scale.

[4] Astrophysical Journal, **9**, 332, 1899.

The local time of each observation, from which the sun's zenith angle and finally the corresponding air mass was computed, was determined from the readings of three watches. Before and after the expedition to Mount Whitney, the watches were compared with the daily telegraphic time signal at Claremont, Cal. The time is probably accurate within half a minute.

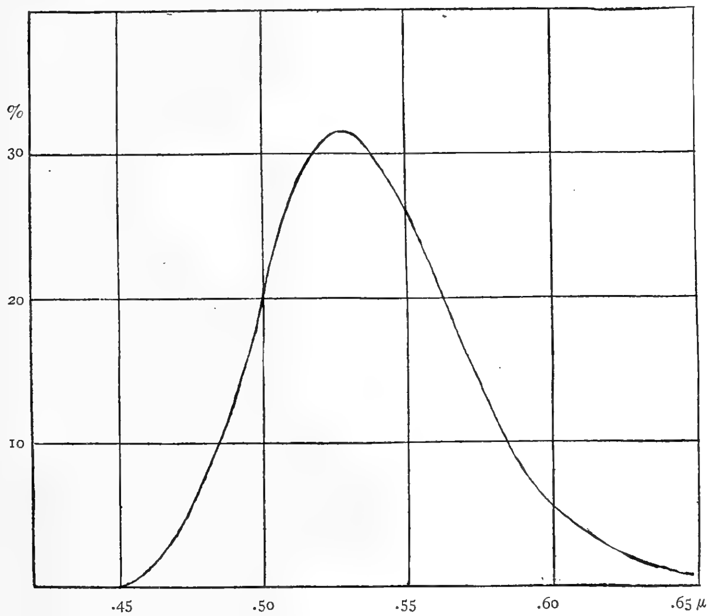

FIG. 16.—Transmission curve of absorbing screen.

RESULTS

The results are given in tables 17 and 18. Table 17 refers to the measurements of the total radiation and contains: (1) the date, (2) the local apparent time (t), (3) the computed air mass (m), (4) readings of the milliammeter (s), (5) the total radiation computed from the readings. Table 18 contains the same quantities relating to measurements taken with the absorbing screen.

Bemporad's[1] expression for the air mass in terms of the apparent zenith angle was employed. His values for 60°, 70°, 80°, and 85° were available in a short table given by F. Lindholm.[2] The differences between these values and the secant of the angle give the (negative) corrections to be applied to the secants of these angles. Through these values of the correction an algebraic curve of four terms was passed and the correction was then calculated for other angles. In obtaining the apparent zenith angle, allowance was made for refraction.

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[1] Mitteilungen der Grossherzoglichen Sternwarte zu Heidelberg, No. 4, 1904.
[2] Nova Acta Reg. Soc., Sc. Upsal., Ser. IV, **3**, No. 6.

TABLE 17.—*Measurements of total radiation*

	t	m	s Milliamp. $\times\frac{1}{3}$	Qm $\frac{\text{cal.}}{\text{cm.}^2\text{min.}}$
	h. m.			
August 2	6 34.2	3.337	100.1	1.224
	6 49.2	2.872	102.5	1.287
	7 30.7	2.088	106.3	1.381
	8 13.2	1.657	108.8	1.446
	9 20.7	1.299	111.3	1.514
August 4	6 28.3	3.630	99.4	1.202
	6 58.8	2.672	104.0	1.322
	7 6.8	2.501	104.1	1.325
	8 4.3	1.741	108.6	1.441
	9 6.8	1.359	110.5	1.493
	11 0.3	1.089	111.7	1.520
	11 8.8	1.081	112.0	1.533
August 5, A. M.	6 29.5	3.608	97.8	1.169
	7 2.0	2.616	103.0	1.296
	7 48.0	1.906	107.0	1.399
	8 59.0	1.397	110.6	1.495
	10 0.5	1.190	111.1	1.508
August 5, P. M.	2 0.3	1.193	111.2	1.511
	3 3.3	1.410	109.5	1.465
	4 4.3	1.830	106.3	1.381
	4 33.8	2.185	104.2	1.326
	5 4.8	2.783	100.1	1.224
	5 24.3	3.377	96.6	1.141
August 10	6 33.0	3.630	95.6	1.117
	7 3.0	2.681	100.5	1.235
	7 56.5	1.857	105.5	1.360
August 11	6 27.1	3.952	96.9	1.147
	6 54.6	2.914	101.9	1.269
	7 40.1	2.053	106.0	1.373
	8 41.6	1.514	109.3	1.460
	10 13.1	1.177	111.7	1.525
August 12	6 26.6	4.018	98.1	1.176
	6 59.1	2.817	103.6	1.312
	7 55.1	1.889	108.5	1.439
	8 57.1	1.435	111.1	1.509
	10 43.6	1.127	113.0	1.561

TABLE 18.—*Measurements with absorbing screen*

	t	m	s Milliamp. ×2	Q_m $\frac{\text{cal.}}{\text{cm.}^2\text{ min.}}$
	h. m.			
August 2	6 18.2	4.044	104.5	0.0371
	6 54.7	2.733	114.1	0.0442
	7 25.7	2.158	122.0	0.0505
	8 22.7	1.589	125.4	0.0534
	8 31.7	1.530	126.8	0.0546
	9 15.2	1.319	128.8	0.0562
August 4	6 16.8	4.204	103.1	0.0361
	6 36.3	3.316	112.1	0.0426
	7 11.8	2.406	118.9	0.0480
	8 9.3	1.699	125.3	0.0533
	9 19.3	1.311	128.0	0.0556
	11 13.3	1.077	129.9	0.0573
August 5 A.M.	6 17.0	4.237	101.8	0.0352
	6 36 0	3.352	108.8	0.0402
	8 3.5	1.755	123.1	0.0515
	9 5.5	1.368	127.9	0.0554
	10 7.0	1.175	129.4	0.0568
August 5 P.M.	2 6.8	1.209	129.3	0.0567
	3 12.8	1.457	126.7	0.0545
	4 11.8	1.907	122.4	0.0509
	4 40.3	2.287	118.3	0.0475
	5 10.3	2.928	114.1	0.0441
	5 30.3	3.615	106.6	0.0386
August 9	6 14.4	4.607	96.0	0.0313
	6 33.9	3.559	103.4	0.0363
	11 38.9	1.126	128.8	0.0563
August 10	6 21.5	4.211	100.6	0.0344
	6 38.0	3.428	106.7	0.0387
	7 8.0	2.570	113.8	0.0439
	8 2.0	1.804	122.4	0.0508
	8 6.0	1.767	122.0	0.0505
August 11	6 14.6	4.716	102.5	0.0356
	6 33.6	3.641	107.9	0.0395
	7 0.1	2.770	114.6	0.0445
	7 45.1	1.992	122.1	0.0507
	8 51.1	1.462	127.1	0.0549
	10 18.6	1.166	129.9	0.0573
August 12	6 13.1	4.895	99.1	0.0333
	6 34.1	3.656	108.0	0.0397
	7 5.1	2.671	116.4	0.0459
	8 3.6	1.804	123.5	0.0517
	9 2.6	1.409	128.1	0.0557
	10 52.6	1.115	131.5	0.0587

GENERAL DISCUSSION OF THE EMPIRICAL METHODS FOR COMPUTING THE SOLAR CONSTANT

Empirical methods for determining the solar constant from pyrheliometric measurements alone have been proposed by K. Ångström [1] and by Fowle.[2] Both these methods are based upon results obtained from spectrobolometric observations. Ångström's method assumes that from Abbot and Fowle's observations we know both the distribution of energy in the sun's spectrum and the general transmission of the atmosphere for all wave lengths in terms of its value for any given wave length. It assumes further that the absorption caused by the water vapor is a known function of the water-vapor pressure at the earth's surface; for this, Ångström proposed an empirical formula based upon his spectrobolometric curves. The influence of diffusion and absorption can then be calculated if the transmission for some chosen wave length is known from pyrheliometric observations on a limited part of the spectrum.

Fowle's method is much briefer. He plots the logarithms of the observations against the air masses and extrapolates to air-mass zero by means of the straight line that best fits the points. To the "apparent solar constant" thus obtained he applies an empirical correction depending upon the locality, and derived from local spectrobolometric observations.

Since these methods are founded upon the spectrobolometric method, one may ask, what is the justification for using them instead of the latter? Can they be expected to give something more than the method upon which they are founded? To the first question one may reply that the justification lies in their simplicity, which makes it possible to apply them under a wide range of conditions where the more cumbersome bolometric method could never be used. A spectrobolometric investigation, like that of Abbot on Mount Whitney in 1910, will probably always be a rare event. But especially in regard to the question of solar variability it is desirable that the number of simultaneous observations be large and extended to as high altitudes as possible.

The second question, whether the abridged methods can ever deserve the same confidence, or even in rare cases give greater accuracy than the spectrobolometric observations, is one that must be answered rather through experimental results than through general considerations. Here, however, two points may be noted.

The first is, that the spectrobolometric method, which under ideal conditions is naturally superior to any abridged method, is in all practical cases a method involving a large number of precautions, some of which are very difficult to take. The abridged methods, founded as they are upon mean values, may possibly under special conditions avoid accidental errors to which single spectrobolometric series are subjected.

Secondly, it may be noted, that even in the analytical method of bolometry, there arises some uncertainty in regard to the ordinates of the bolometric curve, corrected for absorption, at the points where absorption bands are situated. This causes an uncertainty in the water-vapor correction in this method as well as in the abridged methods founded upon it.

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[1] Nova Acta Reg. Soc., Sc. Upsal., Ser. IV, **1**, No. 7.

[2] Annals of the Astrophysical Observatory, Smithsonian Inst., **2**, 114.

The methods just discussed lead to a numerical value for the solar constant. But the measurements in a selected part of the spectrum lead also to a direct test of solar variability, which seems likely to be especially valuable because these observations are not affected by aqueous absorption.

MEASUREMENTS WITH ABSORBING SCREEN

We may put:

$$I = I_0 e^{-\gamma m}$$

where I_0 is the energy transmitted through the absorbing screen at the limit of the atmosphere, I is its value after passing through the air mass m, and γ is a constant dependent upon the scattering power of the atmosphere. If now we plot log I against m, the points should lie on a straight line, whose ordinate for $m = 0$ is log I_0.

The values of I_0 thus obtained from our observations are given under the heading I_0 in table 19. The straight lines were run by the method of least squares, not so much because the presuppositions of this method seemed here to be satisfied, as because thereby all personal bias was eliminated. The "probable error" e of each value of I_0 is appended as a rough indication of its reliability, and the weighted mean I_0 is given at the bottom of the table. A comparison between the different values of I_0 shows that they all differ by less than 2 per cent; half of them by less than ½ per cent from the mean value. The deviation falls as a rule within the limits of the probable error.

This result thus fails to support the variability of the sun inferred by Abbot from simultaneous observations at Bassour and Mount Wilson. We cannot, however, with entire safety draw any conclusions about the total radiation from measurements in a limited part of the spectrum. All that can be said with certainty is that *a change of the energy in the green part of the solar spectrum exceeding 2 per cent during the period of our observations is improbable.*

If we, from this, are inclined to infer that the total solar radiation during the same period was constant, this inclination rests upon a statement by Abbot[1] himself to this effect: "So far as the observations[2] may be trusted, then, they show that a decrease of the sun's emission of radiation reduces the intensity of all wave lengths; but the fractional decrease is much more rapid for short wave lengths than for long."

Yet unpublished measurements by Mr. A. K. Ångström, in Algeria at 1,160 m. altitude, give a mean value for I_0 equal to 0.0708, which is in close agreement with the value 0.0702 given above. On the former occasion Mr. Abbot's spectrobolometric observations gave a mean value for the solar constant of 1.945. If we assume the energy transmitted by our green glass on Mount Whitney to bear the same ratio to the total energy, the Mount Whitney observations give a value for the solar constant reduced to mean solar distance equal to 1.929, which differs by less than 1 per cent from the former value.

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[1] Annals of the Astrophysical Observatory, Smithsonian Institution, **3**, 133. 1913.

[2] Observations of Bassour and Mount Wilson, 1911-1912.

MEASUREMENTS OF THE TOTAL RADIATION

The general basis of the Ångström-Kimball method of calculation has already been described. It is here convenient to make use of the spectrum of constant energy introduced by Langley, where the abscissa represents the energy included between an extreme (ultra-violet) wave length and the wave length corresponding to the abscissa ; the energy-density plotted as ordinate would then be constant. A table giving wave lengths and corresponding abscissæ is given by Kimball.[1]

Referred to such a spectrum, the atmospheric transmission y_x for any wave-length is well represented by the empirical formula

$$y_x = p^{m\delta} x^{nm\phi(\delta)} \tag{1}$$

where x is the abscissa, m the air mass, and δ a quantity dependent upon the scattering power of the atmosphere. Ångström made the natural assumption $\phi(\delta) = \delta$. Kimball[2] finds that $\phi(\delta) = \sqrt{\delta}$ better fits the observations at Washington and Mount Wilson. In the latter case we have,

$$p = 0.93, \qquad n = 0.18$$

Making these substitutions in (1) and integrating,

$$Q_m = Q_0 \int_0^1 0.93^{m\delta} x^{0.18m\sqrt{\delta}} dx$$

or

$$Q_m = Q_0 \frac{0.93^{m\delta}}{1 + 0.18m\sqrt{\delta}}$$

Kimball then adds an empirical correction for the absorption due to water vapor, based upon bolometric measurements at Washington and at Mount Wilson, and finally obtains

$$Q_0 = \frac{Q_m}{\dfrac{0.93^{m\delta}}{1 + 0.18m\sqrt{\delta}} - [0.061 - 0.008\delta + 0.012E_0 m]} \tag{2}$$

where E_0 represents the depth in millimeters to which the earth's surface would be covered by water if all the aqueous vapor were precipitated. We have adopted this expression, *but instead of attempting to determine E_0 from humidity measurements at the earth's surface we have eliminated it between two equations such as (2) involving different air masses.*

Kimball eliminates δ between two such equations. We have, however, followed the original method of K. Ångström and have determined δ for each day from our measurements with the green glass. The energy maximum of the light transmitted by it lies at 0.526 μ (see fig. 1), to which corresponds the abscissa 0.27 in the constant energy spectrum. Hence for the transmitted green light

$$I_m = I_0 0.93^{m\delta} 0.27^{0.18m\sqrt{\delta}}$$

from which δ can be computed. The values of δ thus obtained are given in table 19.

---

[1] Bulletin of the Mount Weather Observatory, **1**, Parts 2 and 4.

[2] Ibid.

In order to compute Q_0, a smooth curve was drawn through the observations and values of Q_m for $m = 1$, 2, and 3 were read off from the curve. These values and the value of δ for the day were inserted in (2) and E_0 then eliminated between the first and second and the first and third of the equations thus obtained. The results are given in table 19 under the headings Q_{12}, Q_{13}; the mean of these for each day is given under $Q_{KÅ}$ and represents the solar constant as obtained for that day by the Ångström-Kimball method.

The mean value of all the measurements, reduced to mean solar distance, is 1.931 $\frac{\text{cal.}}{\text{cm.}^2\,\text{min.}}$ (Ångström scale) or 2.019 (Smithsonian scale). The maximum deviation from the mean is 3 per cent.

TABLE 19.—*Final results*

	p mm.	δ	I_0 cal. / cm.²min.	e per cent	Q_{12} cal. / cm.²min.	Q_{13} cal. / cm.²min.	$Q_{KÅ}$ cal. / cm.²min.	Q_F cal. / cm.²min.
August 2.....	(3.0?)	0.30	0.0689	0.9	1.904	1.886	1.895	(1.820)
August 4.....	3.0	0.28	0.0678	0.9	1.847	1.829	1.838	1.793
August 5. A.M.	2.5	0.32	0.0683	0.3	1.871	1.874	1.873	1.832
August 5. P.M.	2.9	0.32	0.0684	0.8	1.887	1.900	1.894	1.878
August 9.....	......	(0.39)	(0.0688)	.....	....	....	....	....
August 10.....	3.4	0.33	0.0670	0.7	....	1.826	(1.826)	(1.770)
August 11.....	2.2	0.30	0.0685	0.5	1.877	1.870	1.874	1.793
August 12.....	2.0	0.29	0.0685	0.5	1.896	1.888	1.892	1.802

Finally, Fowle's abridged method was applied to the same observations. Sufficient observations are not available for the elaboration of a special correction suited to Mount Whitney. But from the values of δ, it appears that the transmission over Mount Whitney was about the same as over Mount Wilson, where the average value of δ is 0.25; and the water-vapor pressure, the most uncertain factor, was low (2-4 mm.). Hence it may not be devoid of interest to apply here Fowle's rule as elaborated for Mount Wilson, which is: To the "apparent solar constant" obtained by straight-line extrapolation add 2.7 per cent and as many per cent as there are millimeters in the water-vapor pressure. The results thus obtained are given in table 19 under the heading Q_F; the mean water-vapor pressure is given under p.

$$\text{Weighted mean } I_0 = 0.0683 \frac{\text{cal.}}{\text{cm.}^2\ \text{min.}}$$

$$\text{reduced to mean solar distance } I_0 = 0.0702 \frac{\text{cal.}}{\text{cm.}^2\ \text{min.}}$$

(Ångström scale)

$$\text{Mean reduced to mean solar distance: } Q_{KÅ} = 1.931\ (\text{Å.}),$$

$$= 2.019\ (\text{Sm.}) \frac{\text{cal.}}{\text{cm.}^2\ \text{min.}}$$

$$Q_F = 1.872\ (\text{Å.}),$$

$$= 1.960\ (\text{Sm.}) \frac{\text{cal.}}{\text{cm.}^2\ \text{min.}}$$

SUMMARY

Our pyrheliometric observations on the top of Mount Whitney, extending from August 2 to August 12, 1913, have led to the following results:

1. A variation in the solar constant amounting to more than 2 per cent during this time is improbable.

2. The solar constant computed from the measurements in a selected part of the spectrum, reduced to mean solar distance, came out 1.929 $\frac{\text{cal.}}{\text{cm.}^2\text{ min.}}$ (Smithsonian scale), with a possible error of 1.5 per cent. This value is obtained on the assumption that the energy included between 0.484 μ and 0.576 μ is a constant known fraction of the total energy in the solar spectrum.

3. The solar constant computed by the Ångström-Kimball method was found to be 2.019 $\frac{\text{cal.}}{\text{cm.}^2\text{ min.}}$ (Smithsonian).

4. The solar constant computed according to Fowle's method comes out 1.960 $\frac{\text{cal.}}{\text{cm.}^2\text{ min.}}$ (Smithsonian).

The value of the solar constant given in (2) is in close agreement with Abbot's mean value of 1.932 obtained from several series of observations made during the years 1902-1912 at much lower altitudes (*e. g.,* at 1160 m. in Algeria). The value given in (3) is also in close agreement with the solar constant computed by Kimball according to the same method from measurements at Washington. Consequently our observations give no support to a value of the solar constant greatly exceeding 2 $\frac{\text{cal.}}{\text{cm.}^2\text{ min.}}$.

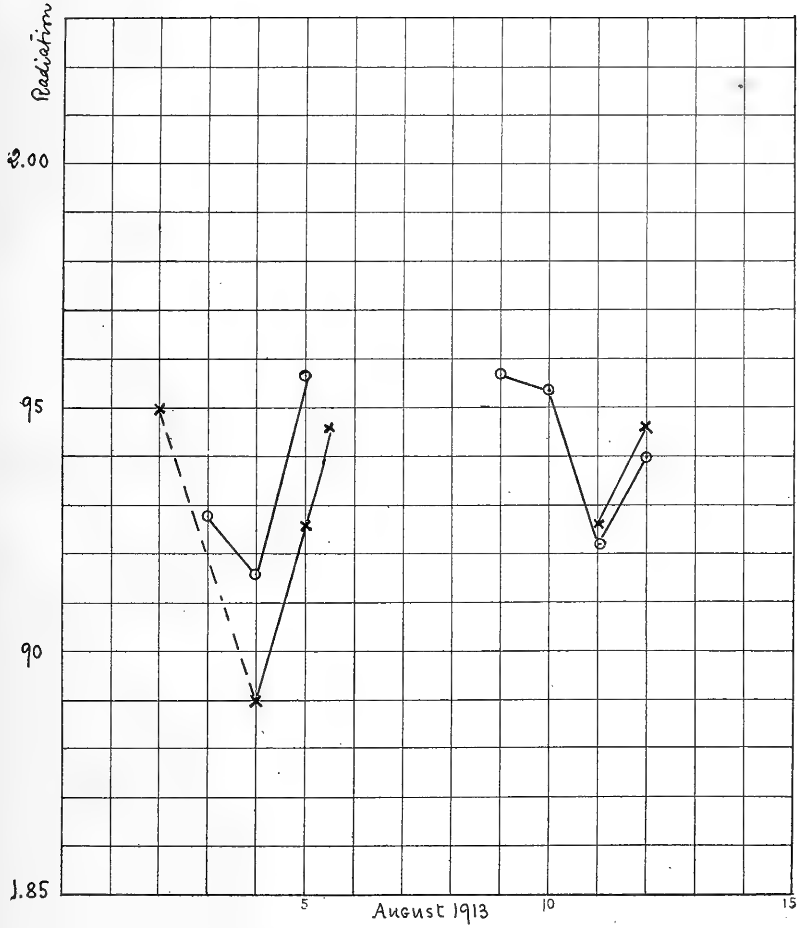
Because of their bearing upon the question of solar variability, it seems desirable that the observations in selected parts of the spectrum by means of absorbing screens should be extended to different localities, and that if possible simultaneous measurements at elevated stations should be undertaken.

Cornell University,
December, 1913.

Note.—After the publication of the paper treating the pyrheliometric observations on Mt. Whitney by Dr. Kennard and myself, the spectrobolometric observations at Mt. Wilson have been published by Dr. Abbot. From both the simultaneous series, it is evident that our observations have been carried out during a period of relatively high constancy of the solar activity. No evidence in regard to the variability of the solar radiation can therefore with safety be drawn from these few observations alone. If the doubtful observations of August 8 and August 10 are excluded, the simultaneous observations at the two places seem, however, to confirm one another very well, as may be seen from figure 17. It seems, therefore, to be probable that the variations in the computed solar constant values are due to a real solar variability, the existence of which is very strongly indicated by the work of several expeditions of the Smithsonian Institution.[1]

Anders Ångström.

[1] Annals II and III of the Astrophysical Observatory of the Smithsonian Institution.



Circles: Mt. Wilson solar constant values.
Crosses: Mt. Whitney solar constant values.

FIG. 17.

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NEW EVIDENCE ON THE INTENSITY OF SOLAR RADIATION OUTSIDE THE ATMOSPHERE

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By C. G. ABBOT, F. E. FOWLE, and L. B. ALDRICH

The following investigations were suggested by several criticisms of the work of the Astrophysical Observatory on the "Solar Constant of Radiation." We shall show: (1) That on fine days at Mt. Wilson there is no observable systematic change of atmospheric transparency from the moment of sunrise to about 10 o'clock, and (2) That the intensity of solar radiation even at 24 kilometers (15 miles) altitude, at less than one twenty-fifth atmospheric pressure, falls below 1.9 calories per square centimeter per minute.

It will be useful to preface the paper by a brief account of our earlier work. We shall draw attention also to various facts tending to support the result heretofore obtained, namely: The mean value of the "solar constant" is 1.93 calories per square centimeter per minute.

SUMMARY OF EARLIER WORK

In Vol. III of the Annals of the Astrophysical Observatory of the Smithsonian Institution, we published the methods employed, the apparatus used, and results obtained in determinations of the mean intensity of solar radiation outside the atmosphere during the years 1902 to 1912. The method employed was that of Langley.[1] It requires measuring the intensity of the total radiation of the sun with the pyrheliometer and also the measurement of the intensity of the rays of the different wave lengths with the spectro-bolometer. Measurements of both kinds are made repeatedly during a clear forenoon or afternoon from the time when the sun is low until it becomes high or vice versa. In this way we determine how rapidly

[1] "Report on the Mount Whitney Expedition," Professional Papers, Signal Service, No. 15, pp. 135 to 142, and table 120, values 1 to 5.

the rays of the sun as a whole and of individual wave lengths in particular increase in intensity as their path in air diminishes. From this we estimate the total intensity of the solar radiation outside the atmosphere altogether.

There are certain parts of the spectrum where by reason of powerful selective absorption of rays by water vapor and other terrestrial atmospheric vapors and gases, sufficiently accurate atmospheric transmission coefficients cannot be determined in this manner.[1] This offers no great difficulty, for, with Langley, we assume that these absorption bands would be absent outside the atmosphere. Hence the intensity of these parts of the spectrum outside the atmosphere can be determined by interpolation from the intensities found on either side of them.

Whatever the value of the atmospheric extinction of solar rays, all good solar constant work depends on accurate pyrheliometry expressed in standard calories.

During the investigation we devised two forms of standard pyrheliometer on quite different principles. These instruments agree with each other to within 0.5 per cent, and they yield values of the solar radiation ranging from 3 to 4 per cent above those found with different copies of the Ångström pyrheliometer. This latter instrument was adopted as the international standard for the measurement of radiation by the meeting of the International Meteorological Committee held at Southport in the year 1903 and by the International Union for Solar Research at its meeting at Oxford in the year 1905. Mr. A. K. Ångström has, however, lately pointed out that the Ångström instrument is subject to slight errors which cause it to read about 2 per cent too low, according to his opinion. If so, this brings the scale of the Ångström within less than 2 per cent of the scale of the Smithsonian Institution. The latter scale is fortified by the fact that in our several standard pyrheliometers it is possible to introduce and determine test quantities of heat. This has been repeatedly done in each of these instruments, and the test quantities of heat have been recovered to within 0.5 per cent.

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[1] Investigations of Fowle showed, however, that transmission coefficients can be obtained even in the great infra-red bands of water vapor, whose employment would practically obliterate the bands outside the atmosphere. Hence we may conclude that if there are diffuse atmospheric bands not easily recognizable, they will be almost exactly allowed for by ordinary transmission coefficients. See Smithsonian Misc. Coll., Vol. 47.

The following table gives the results of nearly 700 measurements of the solar constant of radiation as published in Vol. III of the Annals above cited:[1]

TABLE 1—*Mean Solar Radiation Outside the Atmosphere*

Expressed in standard 15° calories per square centimeter per minute at mean solar distance

Station	Washington	Bassour	Mt. Wilson	Mt. Whitney	Total
Years	1902–1907	1911–1912	1905–1912	1909–1910	......
Altitudes (meters)	10	1,160	1,730	4,420	......
Observations	37	82	573	4	696
Mean result	1.968	1.928	1.933	1.923	1.933

The Washington results fall a little higher than the others. This may be due, in part at least, to the fact that most of them were made while sunspots were numerous, for our investigations at Mt. Wilson indicate that high values prevail when sunspots are at a maximum.

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[1] We note here the following errors which have been found in Vol. III of the Annals, partly by ourselves, and partly by others who have kindly communicated them:

Page 119, figure 11,	Nov. 8 misplotted. Should be 2.004, see p. 105.
Page 129, table 42,	Nov., 1908, for 1.947 read 1.961.
	Under "Mean," for 1.936 read 1.945.
Page 130, figure 16,	Nov., 1908, for 1.947 plot 1.961.
Page 132, table 43,	14th column, for 592 read 607; for 1,338 read 1,363.
	16th column, for —4.4 read —6.6; for —2.1 read —3.9.
Page 134, table 44,	In 1908, for 1.936 read 1.945.
	In "Total," for 1.9315 read 1.9333.
	Under "General mean," for 1.932 read 1.933.
Page 138, table 47,	Wave lengths, for .5995, .7200, .8085, .9215, 1.0640, 1.1474, 1.2230, 1.3800, read .5980, .7222, .8120, .9220, 1.0620, 1.1460, 1.2255, 1.3770.
Page 162, table 58,	We withdraw the conclusion based on this table as to the direction of the change of distribution of solar radiation with change of "solar constant." A great body of as yet unpublished experiments leads to modifications.
Page 201, table.	Under "Intensity," for 1,338 read 4,160.

In regard to the matter mentioned by Kron (Vierteljahr. Astron. Gesell. 49 Jahr., p. 68, 1914), we included in our statement, page 127, two days of 1911 in which the Bassour work was very satisfactory, but the Mt. Wilson work was not. We regret the errors in our figure 15 mentioned by Kron. The principal one is the omission of August 31. Two others are misplotting the Mt. Wilson values for September 4 and September 9. All the corrections improve the appearance of figure 15. See page 122 for the true values.

Our determinations rest on the assumption that for all excellent days the atmosphere may be regarded without sensible error as made up of layers, concentric with the earth, which may differ in transparency from layer to layer in any gradual manner, but which, within the time and space covered by a solar beam during a single morning of observation, are for each layer by itself sensibly of uniform transparency. As the relative transparency of the several layers is not assumed to be known, it is convenient to limit the duration of a single series of observations to the time interval during which the solar zenith distance is less than 75°. During this interval the rate of decrease of path of the solar beam in the atmosphere, with decreasing solar zenith distance, is sensibly the same in all the supposed atmospheric layers, and is proportional to the change of the secant of the zenith distance. For greater zenith distances than these this proportionality does not hold, because of the influences of curvature of the earth and of atmospheric refraction.

Figures 1 and 2, and table 2, show something of the variety of conditions of observation encountered; first, as regarding the intensity of sunlight at the observing station; second, as to the effect of atmospheric humidity on the infra-red spectrum; third, as the effect of dust upon the visible spectrum. We draw attention to the close agreement of the solar constant values obtained in these contrasting circumstances of observation.

TABLE 2—*Variety of Conditions of Observation*

Place	Barometer	Date	Temperature	Atmospheric water vapor pressure at station	Precipitable water[2]	Radiation observed Zenith distance 60°	Transmission coefficient Wave length $\lambda=.5\mu$	Corrected solar constant
	cms.			*mms.*	*mms.*	*calories*		
Washington	76.5	Feb. 15, 1907	3.0	1.45	4.8	1.352	.837	1.872
		May 14, 1907	29.0	14.60	22.6	0.939	.626	2.034
Bassour....	66.3	June 9, 1912	14.0	6.94	12.6	1.302	.855	1.903
		July 26, 1912	26.0	5.36	11.9	0.960	.684	1.915
Mt. Wilson.	62.5	Aug. 21, 1910	23.0	7.39	22.5	1.198	.852	1.933
		Aug. 21, 1911	23.0	2.50	11.2	1.370	.843	1.944
Mt. Whitney	44.7	Sept. 3, 1909	1.0	1.97	(0.90)	1.560	.905	1.951
		Aug. 14, 1910	2.0	2.05	0.60	1.607[1]	.923	1.923[1]

[1] This value is corrected as suggested in note 2, Annals III, page 113.
[2] Determined by Fowle's spectroscopic method, and gives the depth of liquid water which would result if all the atmospheric water vapor above the station should be precipitated. Experiments of 1913 show close agreement of this method in its results with those obtained for the same days by integration of humidity observed at all altitudes by sounding balloons.

From the foregoing the reader may see that the soundness of the theory of the atmospheric extinction of radiation employed by us is supported by the fact that its application to observations made under widely diverse conditions yields nearly identical values of the intensity of solar radiation outside the atmosphere. Nevertheless, it is maintained by some critics that our estimate of the atmospheric extinction is less than half large enough. It seems very singular that a grossly erroneous theory, according to which, however, the

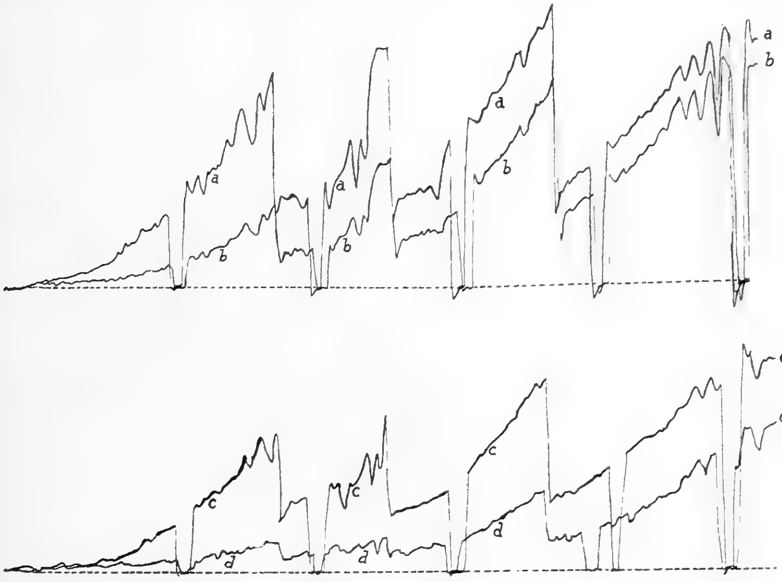

FIG. 1.—Illustrating Atmospheric Extinction on a Clear Day and on a Hazy Day.

Curve *a*, Bassour, June 9, 1912. Air-Mass, 1.5.
Curve *b*, Bassour, June 9, 1912. Air-Mass, 3.5.
Curve *c*, Bassour, July 26, 1912. Air-Mass, 1.6.
Curve *d*, Bassour, July 26, 1912. Air-Mass, 3.5.

transmission coefficients of the atmosphere for green light are found to vary in different circumstances from 0.63 to 0.92, should nevertheless correlate its errors in such a way that all these diverse values of transmission coefficients should lead to equal values of the intensity of solar radiation outside the atmosphere.

In further support of our values of atmospheric transmission, we call attention to their connection with Lord Rayleigh's theory of the scattering of light by molecules and particles small as compared with the wave length of light. According to this the exponent of scattering varies inversely as the fourth power of the wave length, and thus

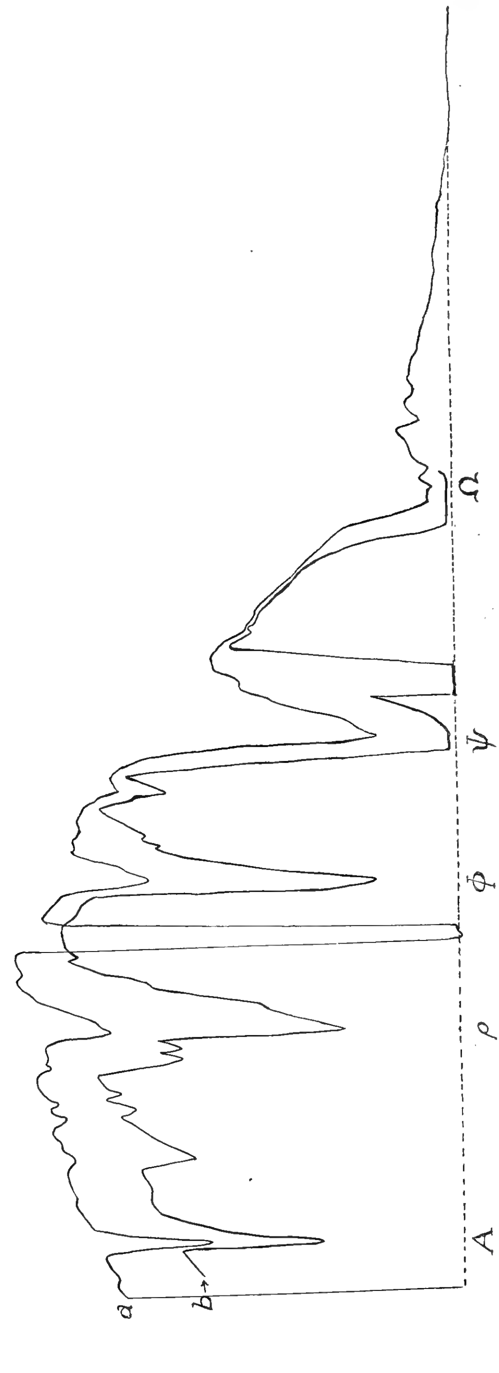

FIG. 2.—Illustrating Absorption of Water Vapor.
Curve *a*, Mt. Whitney, Aug. 15, 1910. Secant $Z = 1.08$.
Curve *b*, Washington, May 14, 1907. Secant $Z = 1.29$.

the product of fourth power of wave length by logarithm of transmission coefficient should be constant. As shown by one of us,[1] the coefficients of atmospheric transmission obtained on Mt. Wilson depend slightly on the total atmospheric humidity included between Mt. Wilson and the sun. The transmission coefficients may be reduced to dry air conditions by applying a very small correction to them. These corrected coefficients, a_0, are found to be in close harmony with Lord Rayleigh's theory, as is shown by the following table. The observed values of a are means for September 20 and September 21, 1914:

Wave length λ in μ	0.3504	0.3709	0.3974	0.4307	0.4753	0.5348	0.5742	0.6858	0.7644
Observed transmission a	.610	.671	.744	.786	.851	.892	.893	.950	.969
Corrected transmission a_0	.632	.686	.752	.808	.863	.898	.905	.959	.979
$\lambda^4 \log a_0$	—30.0	—31.1	—30.9	—31.8	—32.7	—38.2	—46.7	—40.3	—31.4

The deviation from a constant ratio in the yellow and red spectrum is doubtless due to the very large number of atmospheric absorption lines in this part of the spectrum.

By the aid of Lord Rayleigh's theory of the scattering of light, Mr. Fowle has determined from the Mt. Wilson experiments the number of molecules per cubic centimeter of dry air at standard temperature and pressure. He finds the value $(2.70 \pm 0.02) \times 10^{19}$, while Millikan obtained, by wholly dissimilar methods, $(2.705 \pm 0.005) \times 10^{19}$.

In the course of our experiments at Mt. Wilson, we found the solar radiation outside the atmosphere variable in short irregular periods of from five to ten days, and to have a variable range of from 2 to 10 per cent. That this variability is really solar was confirmed by independent simultaneous observing at Bassour in Algeria and still more recently by as yet unpublished experiments on the distribution of brightness over the sun's disk. This latter method is quite independent of atmospheric disturbances. It seems to us that if our solar constant results were erroneous to the extent that the solar constant is really 3.5 calories instead of 1.93, as some of our critics would persuade us, the probability of finding these real solar variations of from 2 to 10 per cent by simultaneous observing at stations separated by one-third of the circumference of the earth would be very small. We should suppose that if there are atmospheric con-

[1] F. E. Fowle, Astrophysical Journal, 38, 392, 1913; 40, 435, 1914.

ditions which lead to our underestimating by nearly 50 per cent the intensity of solar radiation outside the atmosphere, these would probably be variable from day to day; so that such minute real changes of the total intensity of the sun's radiation as we have found would have been swallowed up in the irregular local fluctuations of the transparency of the atmosphere.

CRITICISMS OF THE WORK

We turn from this summary of the work and the circumstances which heretofore indicated its validity, to a discussion of the criticisms which have been made of it by several authors, and the new experiments we have made to refute them. We take the following summaries of objections from several recent articles:[1]

1. Mr. F. W. Very remarks that there are several reliable actinometers, capable, when properly handled, of giving results correct to 1 or 2 per cent, but that unfortunately some of them may give results 20 per cent in error when inefficiently used or imperfectly corrected. Although Mr. Very says in another place that our determinations rest upon perfected instruments and admirable care, yet he has seemed to indicate by his praise of values of the solar radiation obtained from observations on the summit of Mt. Whitney, which reached 2.0 calories per sq. cm. per minute, that he perhaps considers our results to be 15 per cent too low, because in three different years we have never observed on Mt. Whitney values exceeding 1.7 calories per sq. cm. per minute.

2. It is pointed out that we employ the equation[2]

$$\log R = m \log a + \log A$$

as the equation of a straight line. In this equation R is the intensity of one wave length of radiation at the station; A, the corresponding

[1] F. W. Very, Astrophysical Journal, 34, 371, 1911; 37, 25 and 31, 1913; American Journal of Science, 4th Series, 36, 609, 1913; 39, 201, 1915; Bulletin Astronomique, xxx, 5, 1913.

F. H. Bigelow. Boletin de la Oficina Meteorológica Argentina, 3, 69-87, 1912; American Journal of Science, 4th Series, 38, 277, 1914.

E. Kron, Vierteljahrsschrift der Astronomischen Gesellschaft, 49, 53, 1914.

[2] As pointed out by Radau, Langley, and others, this equation is applicable only to homogeneous radiation, that is, radiation of approximately a single wave length. *It is always with this limitation that we employ it in our definitive solar constant determinations.* We have, however, pointed out that for a limited range of two or three air masses good observations of *total* solar radiation, when plotted thus logarithmically, deviate so slightly from the straight line that the smallness of the deviations is a useful guide to the

intensity outside the atmosphere; m, the air-mass, and a the coefficient of atmospheric transmission, assumed as constant. If log a only apparently, not really, is constant, our results are wrong. Both Mr. Very and Mr. Kron indicate pointedly that they believe log a is not constant, but that in fact the transparency of the atmosphere continually diminishes during the forenoon periods we have chosen for our observations, so that our transmission coefficients are too high, and our value of the solar constant too low on account of this source of error. Mr. Kron indicates possible errors of the solar constant values of not more than 5 per cent as due to this cause.

It appears, however, that Mr. Very attaches great weight to this second objection, for he says of the work of Abbot, Fowle, and Aldrich:

> The neglect of diurnal variation of atmospheric quality, and the erroneous supposition that the same coefficients of transmission can be used at all hours of the day, completely vitiate these reductions.

Again he says:

> The Smithsonian observations, for example, usually stop when the air-mass becomes as large as 3 or 4 atmospheres. Some do not even extend to 2 atmospheres. Reduced by Bouguer's formula these mid-day readings agree among themselves, but solely because they have stopped before reaching the point where disagreement begins. This is equivalent to shirking the difficulties, and the seeming extraordinary agreement of the measures is misleading. If the missing readings had been supplied the discrepancies would have been obvious. Such incomplete observations are incapable of elucidating the laws of atmospheric absorption except through the aid of more perfect measures. By supplying deficiencies under guidance of a criterion we may in some cases rescue observations which are, otherwise, useless.

Again he says:

> The portion of the diurnal curve between the limits of 4 and 10 atmospheres conforms tolerably well to the conditions needed for a determination of its slope and general form, and, as a rule, it would seem to be the best part of the curve to select for computation.

3. Mr. Very states that we adopt too high a value of the absorption of terrestrial radiation by water vapor and too low a value of its absorption of solar radiation.

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excellence of the observing conditions. In such applications to pyrheliometry we recognize, however, that A would not be the solar constant. In this connection see figure 3, in which, although for a range of 20 air-masses there is a steady and well-marked curvature in the plot of pyrheliometry, any range of only two air-masses shows this but little. We, therefore, fail to see how Mr. Very's emphatic criticism of our procedure in this respect, which he gives in the French article above cited, is justified.

4. We suppose the layers of air to differ gradually from one to another in transparency. This, according to Mr. Very, may be true for some atmospheric elements, but there are others which are sharply restricted to definite layers or other definitely formed volumes, so that the ordinary air-mass formula fails for this cause.

5. A considerable amount of solar radiation is said by Mr. Very to be definitely lost to measurement in the atmosphere. The Smithsonian observations, he says, give merely the quantity *A—B,* where *B* represents the absorption occurring in fine lines of atmospheric origin, or radiation cut off by particles too gross to diffract the rays, or that which is arrested by bands of absorption not composed of fine lines, but large and diffused, and incapable of being distinguished certainly amidst the crowd of lines and bands which occur in the spectrum.

6. The authors underestimate, according to Very, the solar intensity in the infra-red part of the spectrum where terrestrial rays are sent out. For they suppose the energy there is comparable to that of a "black body" at 6,000°, whereas the sun's radiation is much richer in long waves than that of a body at 6,000°. The solar radiation does not correspond to that of a body of uniform temperature, but its infra-red part corresponds to a body at a higher temperature than does its visible part.

7. Mr. Kron is of the opinion that the authors underestimate the solar radiation in the ultra-violet spectrum, owing to the powerful atmospheric absorption there.

8. Mr. Bigelow finds from thermodynamic considerations that our solar constant values represent the intensity at about 40 kilometers altitude, where the atmospheric pressure is less than $\frac{1}{1000}$ of that at the sea level, but that between this and the limit of the atmosphere the radiation increases from 1.93 to 4.0 calories!

REPLY TO THESE CRITICISMS

First objection.—In regard to (1) we may remark, in addition to what we have said above, that nearly all the pyrheliometry now being done in the world is done with Ångström, Marvin, Michelson, or Smithsonian pyrheliometers. These represent five independent attempts to fix the standard scale of radiation. They have been many times compared with each other, and are found in accord to within less than 4 per cent, and now, in view of A. K. Ångström's researches, perhaps to less than 2 per cent. Of these scales of pyrheliometry, ours gives the highest readings. We have devoted

much experimenting during many years to the establishment of the standard scale of pyrheliometry. Many observers reduce readings obtained with other pyrheliometers to the Smithsonian scale. Dr.

TABLE 3—*Ratios of Transmission Coefficients. Small and Large Air-Masses*

Date	Wave length in microns	.384	.431	.503	.598	.764	1.07	1.45	Mean	Air-mass range small m	Air-mass range large m
Oct. 2, 1910	Ratio $\frac{\text{small } m}{\text{large } m}$	1.080	1.005	0.993	0.968	1.016	0.975	—	**1.006**	1.5–2.5	2.5–3.7
	Ratio $\frac{\text{published } m}{\text{large } m}$	1.031	1.014	.995	.983	1.007	.991	—	**1.003**		
Oct. 6, "	"	.851 .943	.973 .992	1.007 1.005	— —	1.023 1.016	1.021 1.019	— —	**0.975** **0.995**	1.4–2.4	2.4–3.6
Oct. 24, "	"	— —	1.057 1.036	.989 .998	.964 .988	.991 .995	— —	— —	**1.000** **1.004**	1.6–2.6	2.6–3.9
Nov. 6, "	"	.995 .960	.975 .979	1.023 1.012	1.007 1.000	1.000 .997	— —	0.995 1.002	**0.999** **0.992**	1.7–2.8	2.8–4.0
Nov. 7, "	"	1.094 1.019	1.030 1.040	1.038 1.007	1.016 1.026	— —	— —	— —	**1.044** **1.023**	1.7–2.7	2.7–4.2
Nov. 8, "	"	1.016 1.000	1.023 1.016	1.012 1.000	1.028 1.010	.984 .993	— —	— —	**1.013** **1.004**	1.7–2.8	2.8–4.1
Nov. 17, 1911	"	1.109 1.034	1.035 1.014	1.112 1.021	1.026 1.014	1.019 1.007	1.012 1.004	0.964 .991	**1.039** **1.012**	1.7–2.5	2.5–4.3
Nov. 19, "	"	— —	1.002 1.007	.982 1.005	1.030 1.002	1.009 1.007	1.014 1.002	.984 1.007	**1.003** **1.005**	1.7–2.6	2.6–4.4
Oct. 23, 1913	"	1.119 1.063	.957 .999	1.000 1.007	.982 .986	.995 .993	1.014 1.007	1.033 1.024	**1.014** **1.011**	1.5–3.0	3.0–4.5
Oct. 25, "	"	— —	1.007 1.030	1.035 1.019	.998 1.007	1.005 1.002	1.005 1.012	1.040 1.038	**1.015** **1.015**	1.5–2.4	2.4–4.6
Oct. 26, "	"	0.991 1.020	1.042 1.019	1.042 1.012	.989 .989	.995 .998	1.007 1.007	— —	**1.011** **1.007**	1.6–2.4	2.4–4.5
Oct. 28, "	"	1.067 1.035	1.016 .992	1.062 1.002	1.067 1.007	1.038 1.005	.984 .995	1.007 1.007	**1.034** **1.006**	1.6–2.5	2.5–5.0
Nov. 4, "	"	.863 .988	1.007 1.012	.966 .998	1.002 1.008	.982 .997	.980 .998	— —	**0.967** **1.000**	1.6–2.4	2.4–4.7
Nov. 5, "	"	1.054 .975	.977 .994	.968 .986	1.014 1.007	1.002 1.003	.991 .997	— —	**1.001** **0.994**	1.6–2.4	2.4–4.8
Nov. 7, "	"	1.014 1.037	1.014 1.014	.957 .980	1.002 1.004	.993 .998	.984 .995	— .998	**0.994** **1.004**	1.7–2.5	2.5–5.0
Nov. 8, "	"	.865 .938	1.067 1.017	.982 .991	1.028 1.009	1.038 1.002	1.012 1.000	1.005 .995	**1.000** **0.993**	1.7–2.5	2.5–5.2
Means	"	**1.009** **1.003**	**1.012** **1.011**	**1.010** **1.002**	**1.008** **1.003**	**1.006** **1.001**	**1.000** **1.002**	**1.004** **1.008**	**1.007** **1.004**		

Hellmann has indeed gone so far as to say publicly[1] that there is but one standard pyrheliometer, and that is at the Astrophysical Observatory of the Smithsonian Institution.

[1] Bericht über die Erste Tagung der Strahlungskommission des Internationalen Meteorologischen Komites in Rapperswyl bei Zurich, 2 September, 1912.

Second objection.—In view of the great importance attached by Mr. Very and others to the observation of solar radiation at great air-masses, we reexamined some of our observations of former years which were made at larger than the usual air-masses. For each of the days we give in the preceding table ratios of atmospheric transmission coefficients found for different air-mass ranges at many points in the spectrum, first, as obtained by comparing results found at small air-masses with those found at large ones, and, second, by comparing those heretofore published with those now obtained at large air-masses. For the determination of transmission at large air-masses, the observations were replotted, using Bemporad's air-mass tables instead of the secant of the zenith distance. The new plots did not include the observations at small air-masses, thus avoiding any prejudice of the observer which might have been caused by seeing them. The results of the comparison appear in the preceding table. It cannot be said that this indicates any considerable fall of transparency as the air-mass decreases. Had this been the case the ratios given would in general have been greater than unity. The slight tendency in that direction is hardly beyond the error of determination, and, besides, is to be attributed to the departure of Bemporad's air-masses from secant Z values used in our publications heretofore.

OBSERVATIONS OF SEPTEMBER 20 AND SEPTEMBER 21, 1914

For a more thorough test we selected two of the driest and clearest days on which we have ever observed on Mt. Wilson, namely, September 20 and September 21, 1914, for combined spectro-bolometric and pyrheliometric measurements, extending from the moment the sun rose above the horizon[1] until the close of our usual observing period at about 10 o'clock in the forenoon. During this interval we obtained on the first day 11 and on the second day 12 bolographs of the spectrum, extending from wave length $0.34\,\mu$ to wave length $2.44\,\mu$, and we made 33 pyrheliometric determinations of the solar radiation on the first day, and 34 such determinations on the second day. We observed the barometric pressure by means of a recording Richard barograph, and we observed the humidity of the air by means of a ventilated Assmann psychrometer.

The following tables include the barometric, hygrometric, and pyrheliometric data:

[1] We computed the apparent zenith distance of the lower limb of the sun at the instant of the start of the first bolograph on September 20 to be 88° 20′. The apparent zenith distance of the mountain horizon at that point is 88° 28′.

TABLE 4—*Pyrheliometry and Meteorological Observations*

Mt. Wilson, Cal., September 20, 1914

Hour angle	Barometer	Temperature		Pressure water vapor	Air-mass	Pyrheliometer readings		Precipitable water vapor
		Dry	Wet		(Bemporad)	IV	VII	(Fowle)
E h. m.	*cm.*	°	°	*mm.*		*calories*[1]	*calories*[1]	*mm.*
6 06	....	16.5	9.7	6.11	....	....	....	....
5 54.8	61.9	....	....	....	19.31	0.530	....	....
53.8	....	....	....	....	18.32	....	0.558	....
50.8	....	....	....	....	15.82	.620	....	3.3
49.8	....	....	....	....	15.10	....	.636	....
46.8	....	....	....	....	13.89	.676	....	....
45.8	....	....	....	....	13.33	....	.708	....
42.8	....	....	....	....	11.44	.768	....	....
41.8	....	....	....	....	11.03	....	.776	4.0
38.8	....	....	....	....	9.97	.814	....	....
37.8	....	....	....	....	....	....	....	....
34.8	....	....	....	....	8.82	.883	....	....
33.8	....	....	....	....	8.57	....	.900	....
30.8	....	....	....	....	7.91	.922	....	....
29.8	....	....	....	....	7.71	....	.951	....
26.8	....	....	....	....	7.16	.976	....	4.1
25.8	....	....	....	....	7.00	....	.979	....
14.8	....	....	....	....	5.52	1.082	....	4.6
13.8	....	....	....	....	5.42	....	1.093	....
8	....	16.7	9.4	5.71	5.05	....	....	....
4.8	....	....	....	....	4.67	1.146	....	....
3.8	....	....	....	....	4.59	....	1.143	4.9
4 48.8	....	....	....	....	3.74	1.232	....	....
47.8	....	....	....	....	3.69	....	1.229	....
44.8	....	....	....	....	3.56	1.242	....	5.2
43.8	....	....	....	....	3.52	....	1.262	....
39	....	17.4	8.6	4.62	3.35	....	....	....
32.8	....	....	....	....	3.11	1.292	....	....
31.8	....	....	....	....	3.08	....	1.291	5.9
9.8	....	....	....	....	2.53	1.371	....	....
8.8	62.0	....	....	....	2.51	....	1.407	5.0
3 44	....	18.2	12.2	8.06	2.108	....	....	....
38.8	....	....	....	....	2.044	1.435	....	....
37.8	....	....	....	....	2.032	....	1.439	5.8
2 50.8	....	....	....	....	1.615	1.496	....	....
49.8	....	....	....	....	1.609	....	1.497	6.6
44	....	20.2	14.1	9.41	1.573	....	....	....
2.8	....	....	....	....	1.383	1.516	....	....
1.8	....	....	....	....	1.380	....	1.516	8.6
1 56	62.0	21.4	15.0	9.99	1.360	....	....	....

[1] See Note 1, Table 9.

TABLE 5—*Pyrheliometry and Meteorological Observations*

Mt. Wilson, Cal., September 21, 1914

Hour Angle	Barometer	Temperature		Pressure water vapor	Air-mass	Pyrheliometer readings		Precipitable water vapor
		Dry	Wet		(Bemporad)	IV	VII	(Fowle)
E h. m.	*cm.*	°	°	*mm.*		*calories* [1]	*calories* [1]	*mm.*
6 00	....	15.4	5.1	2.21	....	....	....	....
5 54.8	62.1	....	....	....	20.36	0.489	....	....
53.8	....	....	....	....	19.34	....	0.523	....
50.8	....	....	....	....	16.62	.578	....	3.8
49.8	....	....	....	....	15.85	....	.616	....
46.8	....	....	....	....	13.89	.655	....	....
45.8	....	....	....	....	13.33	....	.689	....
42.8	....	....	....	....	11.86	.719	....	....
41.8	....	....	....	....	11.42	....	.755	4.9
38.8	....	....	....	....	10.31	.788	....	....
37.8	....	....	....	....	9.98	....	.798	....
34.8	....	....	....	....	9.10	.844	....	....
33.8	....	....	....	....	8.84	....	.857	....
30.8	....	....	....	....	8.12	.880	....	6.1
29.8	....	....	....	....	7.91	....	.903	....
26.8	....	....	....	....	7.33	.914	....	....
25.8	....	....	....	....	7.16	....	.944	....
20	....	17.2	8.0	4.12	....	....	....	6.5
15.8	....	....	....	....	5.76	1.027	....	....
14.8	....	....	....	....	5.66	....	1.049	....
11.8	....	....	....	....	5.34	1.061	....	....
10.8	....	....	....	....	5.25	....	1.086	7.1
4 58.8	....	....	....	....	4.32	1.148	....	....
57.8	....	....	....	....	4.25	....	1.163	....
52	....	17.1	6.2	2.48	4.00	....	....	7.2
41.8	....	....	....	....	3.46	1.248	....	....
40.8	....	....	....	....	3.42	....	1.250	7.4
26.8	....	....	....	....	2.97	1.297	....	....
25.8	....	....	....	....	2.94	....	1.312	7.5
15	....	17.7	7.1	3.06	2.67	....	....	....
5.8	....	....	....	....	2.47	1.366	....	....
4.8	62.15	....	....	....	2.45	....	1.370	8.0
3 42	....	18.4	10.3	5.92	2.097	....	....	....
35.8	....	....	....	....	2.022	1.419	....	....
34.8	....	....	....	....	2.010	....	1.438	8.2
2 51	....	20.3	10.9	5.74	1.625	....	....	....
47.8	....	....	....	....	1.606	1.492	....	....
46.8	....	....	....	....	1.600	....	1.498	8.7
2 00	6.22	22.2	13.2	7.49	1.381	....	....	....
1 49.8	....	....	....	....	1.348	1.529	....	....
48.8	....	....	....	....	1.345	....	1.533	8.3

[1] See Note 1, Table 9.

The two days, September 20 and September 21, are in almost complete agreement in every feature observed, except that the atmospheric humidity of September 21 slightly exceeded that of September 20, and this of course led to a slight difference in pyrheliometry. We give below our reduction of the spectro-bolometric work of September 20, and the circumstances of the observations will be found so completely set forth that if any readers should desire, they can re-reduce the day's work for themselves.

It is the principal aim of the investigation to determine if there was on these two days a systematic change of atmospheric transparency sufficient to vitiate solar constant values obtained by our usual method. Referring to our Annals, Vol. II, page 14, it may be shown that for solar zenith distances less than 70° the intensities of homogeneous rays observed at different zenith distances should be expressible by the relation:

$$\log e = \text{secant } z \log a + \log e_0$$

where e is the observed intensity of a homogeneous ray; e_0 its intensity outside the atmosphere; z the zenith distance of the sun; a a constant representing the fraction $\frac{e_1}{e_0}$ in which e_1 is the intensity which would correspond to $z=0$. The above equation being the equation of a straight line, the test of the uniformity of transparency depends on the closeness with which the logarithmic plots for individual wave lengths approximate straight lines.

For zenith distances much greater than 70° the function secant z must be replaced by another, $F(z)$, representing the ratio of the effective length of path of the beam in the atmosphere to that which corresponds to $z=0$. This quantity, $F(z)$, has been determined by Bemporad,[1] taking into account the curvature of the earth, the

[1] Mitteilungen der Grossh. Sternwarte zu Heidelberg IV, 1904. The following illustrates a computation of air-mass $F(z)$.

Example of Air-Mass Computation

For mean 120° meridian time:

1914, Sept. 20, $5^h\ 51^m\ 0^s$ (*i. e.*, $1^m\ 50^s$ after start of first bolograph).

Barometer 24.4 inches = 620 mm.		Temperature = 60° F. = 16° C.	
Longitude	118° 3′ 34″ W.	Equation of time	$+\ 6^m\ 22^s$
Latitude, ϕ,	34° 12′ 55″ N.	Correction for longitude	$+\ 7^m\ 46^s$
			$+\ 14^m\ 8^s$
⊙ Declination, δ,	1° 17′ 28″ N.	Apparent time	$6^h\ 5^m\ 8^s$
Hour angle, t,	88° 43′ 0″ E.	Hour angle	$5^h\ 54^m\ 52^s$

Sun's true altitude h:

Sin $h = \sin\phi \sin\delta + \cos\phi \cos\delta \cos t$ $\qquad h = 1°\ 47'\ 14''$

Sun's true zenith distance $\qquad$ 88° 12′ 46″

atmospheric refraction, and the fall of temperature and barometer with elevation. His assumption regarding the rate of fall of temperature is not quite in accord with recent balloon work, and this leads him to values of $F(z)$ slightly too high, but this error would not exceed 0.5 per cent. As is well known, the atmospheric refraction is uncertain very near the horizon, so that it cannot be expected that the air-masses obtained with apparent zenith distances of 88°, computed from hour angles of observation, should be perfectly accurate.

Strictly, we should determine the value, $F(z)$, to correspond to the apparent center of intensity of the sun's light emission at the proper instant for every wave length, for on account of atmospheric extinction and refraction this is not coincident with the center of form of the sun. But we have found the correction to be always less than 0.5 per cent, and have neglected it.

A far more important consideration relates to the distribution in the atmosphere of the materials which diminish the intensity of sunlight, as the zenith distance increases. Bemporad's discussion assumes that the atmosphere is of uniform optical quality from top to bottom, so that equal masses of it transmit equal fractions of incident light. The researches of Schuster, Natanson, King, Fowle, and Kron show that on clear days at Mt. Wilson the atmospheric extinction, for a large part of the spectrum, seems to be in almost complete accord with the requirements of Rayleigh's theory of scattering. Where this holds, Bemporad's assumption also holds good. But it appears distinctly from Fowle's researches that in certain parts of the spectrum, notably in the yellow, red, and infrared, the atmospheric extinction is partly or mainly attributable to water vapor, or substances which accompany it. These atmospheric constituents, being mainly at low altitudes, require special consideration. We give in the following paragraphs our solution of this difficulty.

By Crawford's tables (Lick Observatory *Publications,* Vol. VII):

If apparent zenith distance is 87° 50′,	Refr. = 13′ 46″
If apparent zenith distance is 87° 58′,	Refr. = 14′ 14″
Hence assume	Refr. = 14′ 16″
Whence sun's apparent zenith distance is	87° 58′ 30″

By Bemporad's air-mass tables:

If apparent zenith distance is 87° 58′ 30″,	$F(z) =$ 19.650
But if $B = 620$, $T = 16°$	$F^1(z) - F(z) = -0.433$
Hence air-mass, $F^1(z)$,	$=$ 19.216

Fowle has determined transmission coefficients similar in their application to the values a given above, but dependent on the total quantity of precipitable water in the atmosphere as determined spectroscopically. He gives the following values of the transmission coefficients for dry air ($a_{a\lambda}$) and for the equal of 1 cm. of liquid as water vapor ($a_{w\lambda}$) above Mt. Wilson. We employ values obtained from observations of 1910 and 1911, in preference to later ones, because obtained prior to the volcanic eruption of 1912.

TABLE 6—*Coefficients of Transmission for the Dry Atmosphere and for Atmospheric Water Vapor (Fowle)*

Wave length λ	.350	.360	.371	.384	.397	.413	.431	.452	.475	.503	.535	.574	.598	.624
$a_{a\lambda}$	.632	.655	.686	.713	.752	.783	.808	.840	.863	.885	.898	.905	.913	.929
$a_{w\lambda}$	.917	.940	.959	.959	.962	.965	.968	.967	.973	.976	.980	.974	.978	.977

Wave l'gth λ.	.653	.686	.722	.764	.812	.864	.987	1.146	1.302	1.452	1.603
$a_{a\lambda}$	.938	.959	.970	.979	.980	.982	.987	.987	.986	.989	.983
$a_{w\lambda}$	.987	.985	.989	.985	.990	.989	.991	.988	.990	.988	.986

These water vapor coefficients apply to smoothed energy curves, and are a measure of the general extinction associated with water vapor apart from its selective absorption.

By Rayleigh's theory the dry air coefficients may be calculated from the known number of molecules of air per cm.³ at standard temperature and pressure. This computation is in close accord with the values above given. We hold therefore that Rayleigh's theory of scattering would yield proper values of general atmospheric extinction, for clear days on Mt. Wilson, if water vapor were absent. As our observed general transmission coefficients in the infra-red spectrum are somewhat less accurate than elsewhere, owing to the necessity of interpolating the curves over the water vapor bands, and from other causes, we have thought it right to compute by Rayleigh's theory the true transmission coefficients in this region as they would be if molecular scattering alone were the active agent.

TABLE 7—*Computed Atmospheric Transmission and Extinction Coefficients*

Wave length...	.764	.812	.864	.922	.987	1.062	1.146	1.226	1.302	1.377
Computed $a_{a\lambda}$..	.979	.9838	.9873	.9903	.9925	.9954	.9959	.9969	.9975	.9980
$1-a_{a\lambda}$	.021	.0162	.0127	.0097	0075	.0046	.0041	.0031	.0025	.0020
$1-a_{\frac{w}{2}\lambda}$	.007	.005	.005	.005	.005	.005	.005	.005	.005	.010

As appears above, the computed transmission for wave lengths exceeding 1.37 μ is approximately unity, and the computed atmospheric extinction coefficient, as given in line 3, sensibly zero. Line 4 gives the general extinction for 0.5 centimeter of precipitable water vapor, corresponding to the humidity of September 20, 1914.

We are now in position to determine a correction to $F(z)$ as given by Bemporad. If the extinction were all molecular scattering, his values would be the true ones. If it were all due to water vapor, we ought to employ approximately secant z, because of the low level of water vapor. We have therefore determined for each wave length the weighted mean between Bemporad's $F(z)$ and secant z, giving weights in proportion to the numbers $(1 - a_{a\lambda})$ and $(1 - a_{\frac{w}{2}\lambda})$ for wave lengths less than 0.764 μ, and in proportion to the numbers $(1 - a_{c\lambda})$ and $(1 - a_{\frac{w}{2}\lambda})$ for wave lengths exceeding 0.764 μ. In one case we have made an exception, namely, for wave length 2.348 μ, which is within the band of carbon dioxide absorption. As this gas forms a nearly constant percentage of the atmosphere up to a level of more than 10,000 meters, we have used Bemporad's $F(z)$ at this wave length. In figures 3 and 4 the reader will see plotted the air-masses as used, and also the lesser air-masses corresponding to Bemporad's $F(z)$.

The following are the circumstances of the spectro-bolometric observations of September 20, 1914:

Extent of spectrum observed (in arc) 270′. Bolometer subtends 17″. Slit subtends 50″.

Extent of spectrum observed in wave lengths: $\lambda = 0.342\ \mu$ to $\lambda = 2.348\ \mu$.

Time elapsing after start $0^m\ 30^s$ to $7^m\ 15^s$.

Bolograph No.	1	2	3	4	5	6	7	8	10[1]	11
Time of start; 120th meridian mean time	*h. m. s.* 5 49 10	*h. m.* 5 59	*h. m.* 6 12	*h. m.* 6 25	*h. m.* 6 40	*h. m.* 6 55	*h. m.* 7 11	*h. m.* 7 33	*h. m.* 8 52	*h. m.* 9 40

Latitude, 34° 12′ 55″ N. Longitude, 118° 3′ 34″ W. Altitude, 1,727 meters.

[1] Bolograph 9 omitted because of interference of a guy wire.

In accordance with our usual course, described in Vol. III of our Annals, we measured the ordinates of smoothed curves on all the bolographs at 38 wave lengths. These were equally spaced in prismatic deviation, excepting that in a portion of the infra-red spectrum we observed at points twice as close together as in the other parts of the spectrum. Table 8 includes the measured ordinates of the smoothed curves (unit 0.1 mm.) and corresponding air-masses, according to Bemporad, for September 20. Our corrected air-masses appear only on figures 3 and 4. The third column of the table gives the factor to reduce to uniform scale throughout the spectrum.

TABLE 8—*Air-masses and Smoothed Curve Ordinates*

Bolographs of September 20, 1914

Prismatic deviation from ω_1	Wave length	Correcting factor[1] for transmission through optical apparatus	Bolograph I		Bolograph II		Bolograph III[3]		Bolograph IV		Bolograph V		Bolograph VI		Bolograph VII		Bolograph VIII		Bolograph X[4]		Bolograph XI	
			Galvanometer deflection[2]	Air-mass (Bemporad)	Deflection[2]	Air-mass (Bemporad)	Deflection[2]	Air-mass (Bemporad)	Deflection[2]	Air-mass (Bemporad)	Deflection[2]	Air-mass (Bemporad)	Deflection[2]	Air-mass (Bemporad)	Deflection[2]	Air-mass (Bemporad)	Deflection[2]	Air-mass	Deflection[2]	Air-mass	Deflection[2]	Air-mass
′	μ																					
240	0.342	.352	[5]	....	[5]	....	[5]	....	[5]	....	28	4.68	50	3.80	50	3.15	100	2.57	150	1.63	165	1.39
230	.350	.215	....	....	....	....	17	8.31	?30	6.14	72	4.67	108	3.79	148	3.14	212	2.56	340	1.63	365	1.39
220	.360	.139	....	....	....	....	41	8.26	?77	6.10	158	4.65	228	3.78	315	3.14	440	2.56	660	1.63	690	1.39
210	.371	.317	....	....	....	....	30	8.21	?70	6.07	90	4.63	132	3.77	196	3.13	240	2.55	345	1.63	370	1.39
200	.384	.270	....	....	....	....	46	8.16	111	6.02	152	4.61	217	3.75	290	3.12	356	2.55	530	1.62	553	1.39
190	.397	.264	....	....	30	12.3	131	8.12	244	5.99	350	4.59	453	3.74	500	3.11	630	2.55	840	1.62	860	1.39
180	.413	.630	....	....	40	12.2	92	8.07	160	5.96	210	4.58	280	3.73	338	3.10	390	2.54	510	1.62	520	1.38
170	.431	.584	?15	18.8	59	12.1	143	8.01	240	5.93	323	4.55	393	3.72	456	3.10	545	2.54	642	1.62	663	1.38
160	.452	.544	?36	18.5	126	12.0	94	7.95	440	5.89	562	4.53	650	3.70	740	3.09	845	2.53	1012	1.62	1033	1.38
150	.475	1.53	?33	18.3	79	11.9	153	7.91	220	5.86	268	4.52	320	3.69	345	3.08	380	2.53	443	1.62	447	1.38
140	.503	1.43	68	18.1	140	11.8	228	7.87	305	5.82	369	4.50	417	3.68	452	3.07	499	2.52	548	1.61	558	1.38
130	.535	1.33	100	17.9	223	11.6	340	7.80	430	5.80	497	4.48	550	3.67	595	3.06	648	2.52	716	1.61	709	1.38
120	.574	1.24	151	17.6	304	11.5	427	7.75	568	5.77	618	4.46	680	3.66	740	3.06	798	2.51	890	1.61	884	1.38
115	.598	1.20	220	17.5	377	11.5	528	7.73	650	5.75	708	4.45	780	3.65	838	3.05	897	2.51	983	1.61	973	1.38
110	.624	1.16	293	17.4	460	11.4	637	7.71	738	5.74	804	4.44	870	3.65	930	3.05	992	2.51	1062	1.61	1063	1.38
105	.653	1.12	425	17.3	608	11.4	780	7.69	896	5.73	950	4.44	990	3.64	1055	3.05	1110	2.51	1178	1.61	1164	1.38
100	.686	1.09	580	17.2	773	11.3	942	7.64	1045	5.71	1096	4.42	1143	3.64	1187	3.04	1238	2.50	1293	1.61	1266	1.38
95	.722	1.07	687	17.1	872	11.3	1033	7.63	....	5.69	1176	4.42	1210	3.63	1245	3.04	1296	2.50	1336	1.61	1312	1.38
90	.764	1.06	783	17.0	950	11.2	1093	7.61	....	5.69	1208	4.41	1244	3.62	1265	3.03	1310	2.50	1345	1.60	1317	1.38
85	.812	1.10	826	16.9	969	11.2	1102	7.59	....	5.68	1192	4.40	1225	3.62	1250	3.03	1294	2.49	1308	1.60	1277	1.38
80	.864	1.17	850	16.8	966	11.1	1086	7.56	....	5.66	1158	4.39	1183	3.61	1200	3.03	1243	2.49	1250	1.60	1220	1.38
75	.922	1.24	834	16.7	948	11.1	1046	7.54	....	5.65	1108	4.38	1120	3.60	1138	3.02	1170	2.49	1180	1.60	1144	1.38
70	.987	1.29	807	16.6	912	11.0	987	7.52	1010	5.63	1030	4.37	1040	3.60	1057	3.02	1098	2.49	1092	1.60	1063	1.38
65	1.062	1.28	719	16.5	830	11.0	878	7.50	913	5.62	920	4.37	920	3.60	943	3.02	960	2.48	978	1.60	947	1.38
60	1.146	1.26	626	16.4	732	10.9	770	7.47	813	5.60	819	4.36	820	3.59	840	3.01	852	2.48	860	1.60	846	1.38
55	1.226	1.23	543	16.3	652	10.9	688	7.45	714	5.59	722	4.35	727	3.58	742	3.01	758	2.48	759	1.60	752	1.37
50	1.302	1.20	489	16.2	580	10.8	613	7.43	626	5.58	650	4.34	640	3.58	662	3.00	673	2.48	690	1.60	660	1.37
45	1.377	1.17	452	16.1	519	10.8	546	7.41	560	5.57	580	4.34	577	3.58	589	3.00	600	2.47	623	1.60	580	1.37
40	1.452	1.14	420	16.0	478	10.7	498	7.37	503	5.55	520	4.32	516	3.57	528	3.00	535	2.47	560	1.60	510	1.37
35	1.528	1.12	392	15.9	436	10.7	448	7.35	455	5.53	465	4.31	463	3.56	470	2.99	475	2.47	488	1.60	466	1.37
30	1.603	.363	1100	15.8	1190	10.7	1240	7.33	1237	5.52	1268	4.31	1270	3.56	1280	2.99	1286	2.47	1311	1.60	1240	1.37
25	1.670	.356	982	15.7	1065	10.6	1111	7.31	1103	5.52	1130	4.30	1132	3.56	1144	2.99	1150	2.46	1178	1.60	1110	1.37
20	1.738	.353	862	15.6	935	10.6	977	7.28	980	5.50	992	4.29	998	3.55	1008	2.98	1011	2.46	1038	1.59	978	1.37
10	1.870	.370	620	15.5	682	10.5	708	7.25	718	5.47	720	4.28	722	3.54	730	2.97	733	2.45	758	1.59	720	1.37
0	2.000	.422	375	15.2	432	10.4	440	7.19	452	5.44	442	4.26	447	3.53	453	2.97	460	2.45	474	1.59	453	1.37
—10	2.123	.176	580	15.1	660	10.3	670	7.16	695	5.42	670	4.24	700	3.52	700	2.96	710	2.45	730	1.59	700	1.37
—20	2.242	.239	272	15.0	318	10.2	335	7.12	350	5.40	350	4.23	355	3.51	360	2.96	365	2.45	390	1.59	375	1.37
—30	2.348	.307	120	14.8	155	10.1	180	7.07	210	5.38	210	4.21	220	3.50	220	2.95	240	2.44	260	1.59	245	1.37

[1] This factor includes consideration of rotating sectors used, reflecting power of coelostat, and transmission in spectroscope.

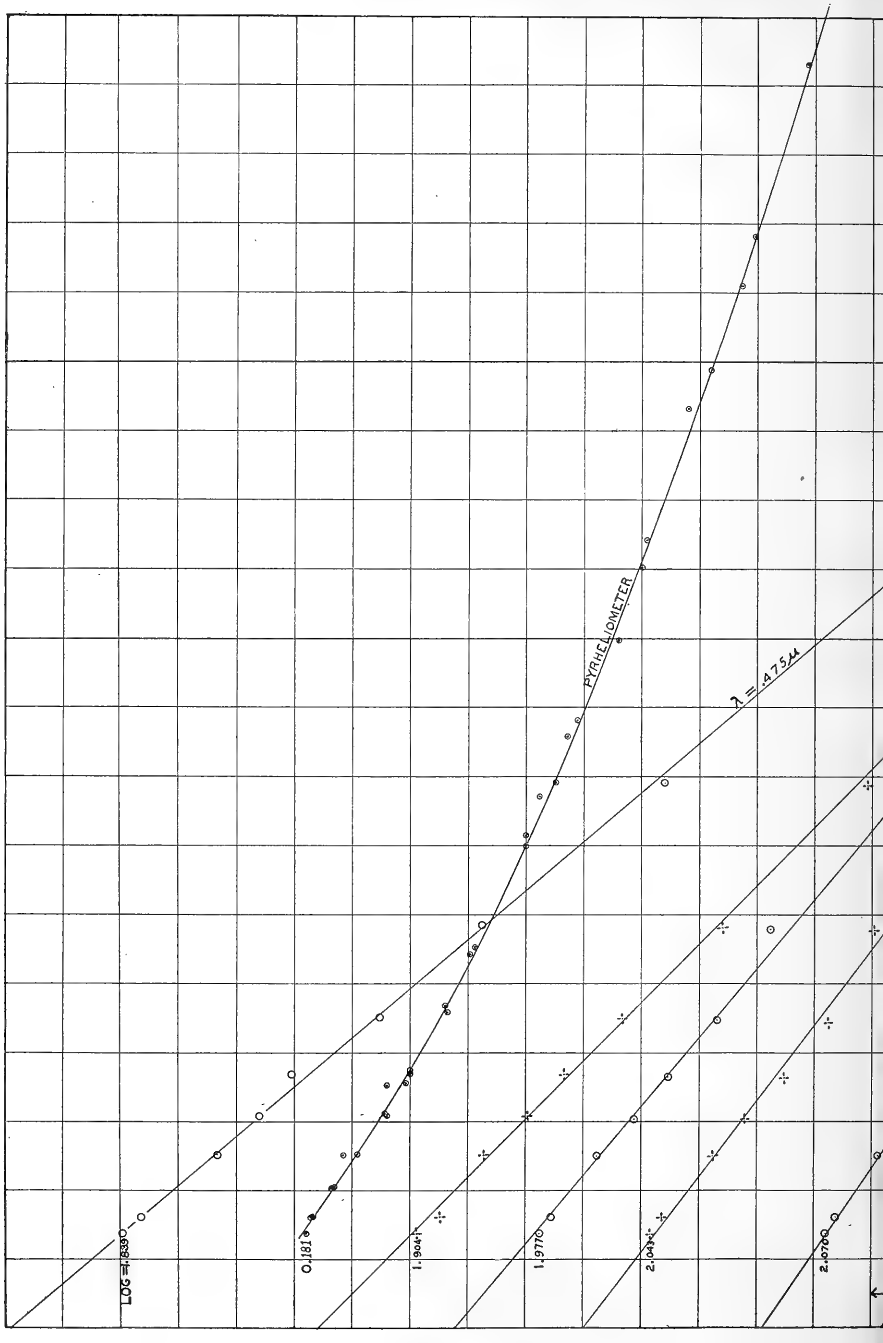
[2] Galvanometer deflections are here expressed in tenths of millimeters.

[3] Bolograph III is a little low in a few points by interference of leaves of a tree.

[4] Bolograph IX is omitted because a guy wire interfered.

[5] Extremely doubtful points, and those for which deflections are less than 1 millimeter, are omitted.

After reducing the measured ordinates (by means of factors given) for transmission in the apparatus, in accordance with the practice of Langley and ourselves, we corrected these new ordinates of the bolographs for the slight changes of sensitiveness of the bolometric apparatus. We determined these changes of sensitiveness by comparing the areas included under the bolographic curves with the


PYRHELIOMETER
λ = .475μ
LOG = 1.839
0.181
1.904
1.977
2.043
2.070

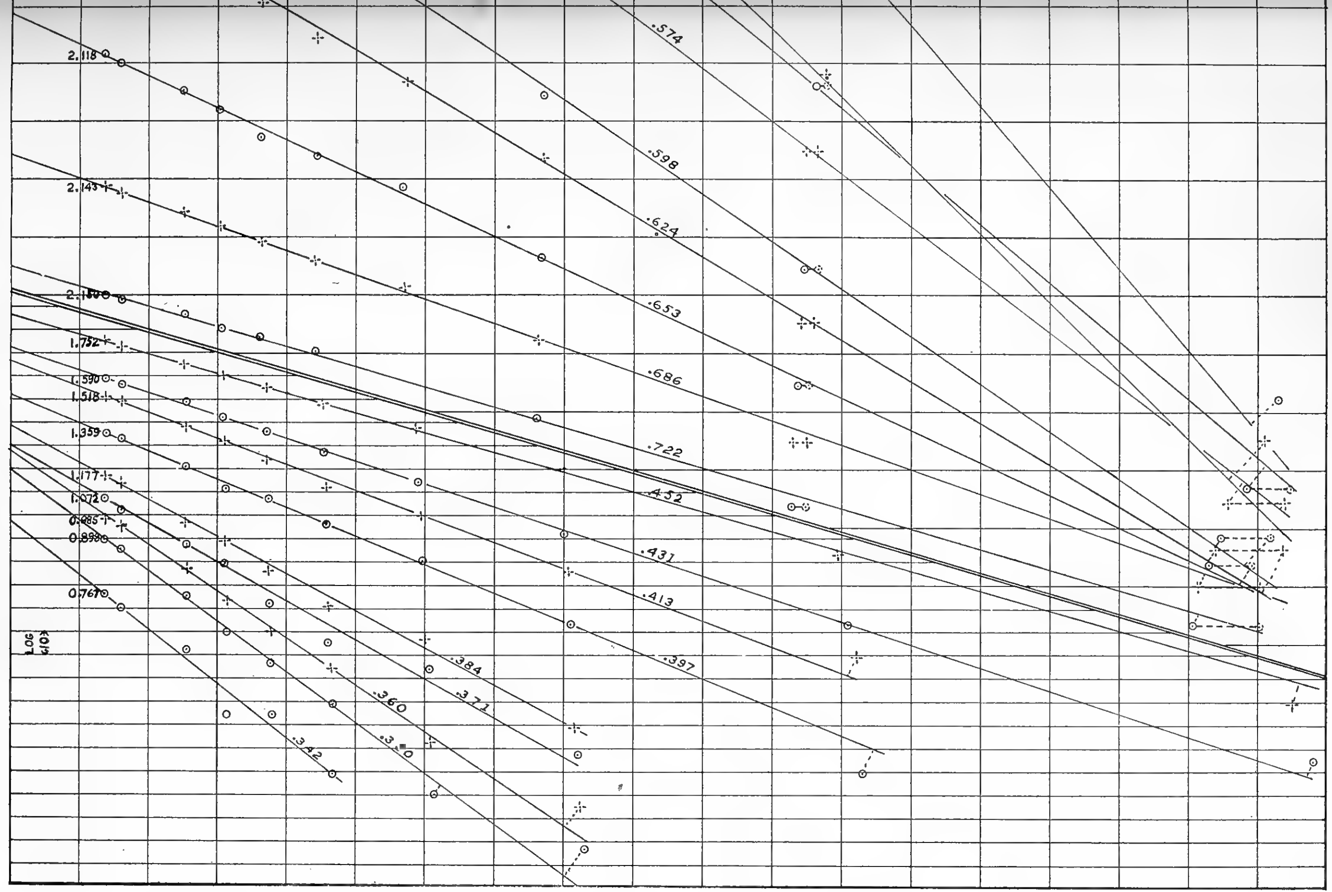


FIG. 3.—LOGARITHMIC CURVES OF ATMOSPHERIC TRANSMISSION. MT. WILSON, SEPT. 20, 1914. NOTE THE TWO SCALES OF ORDINATES.

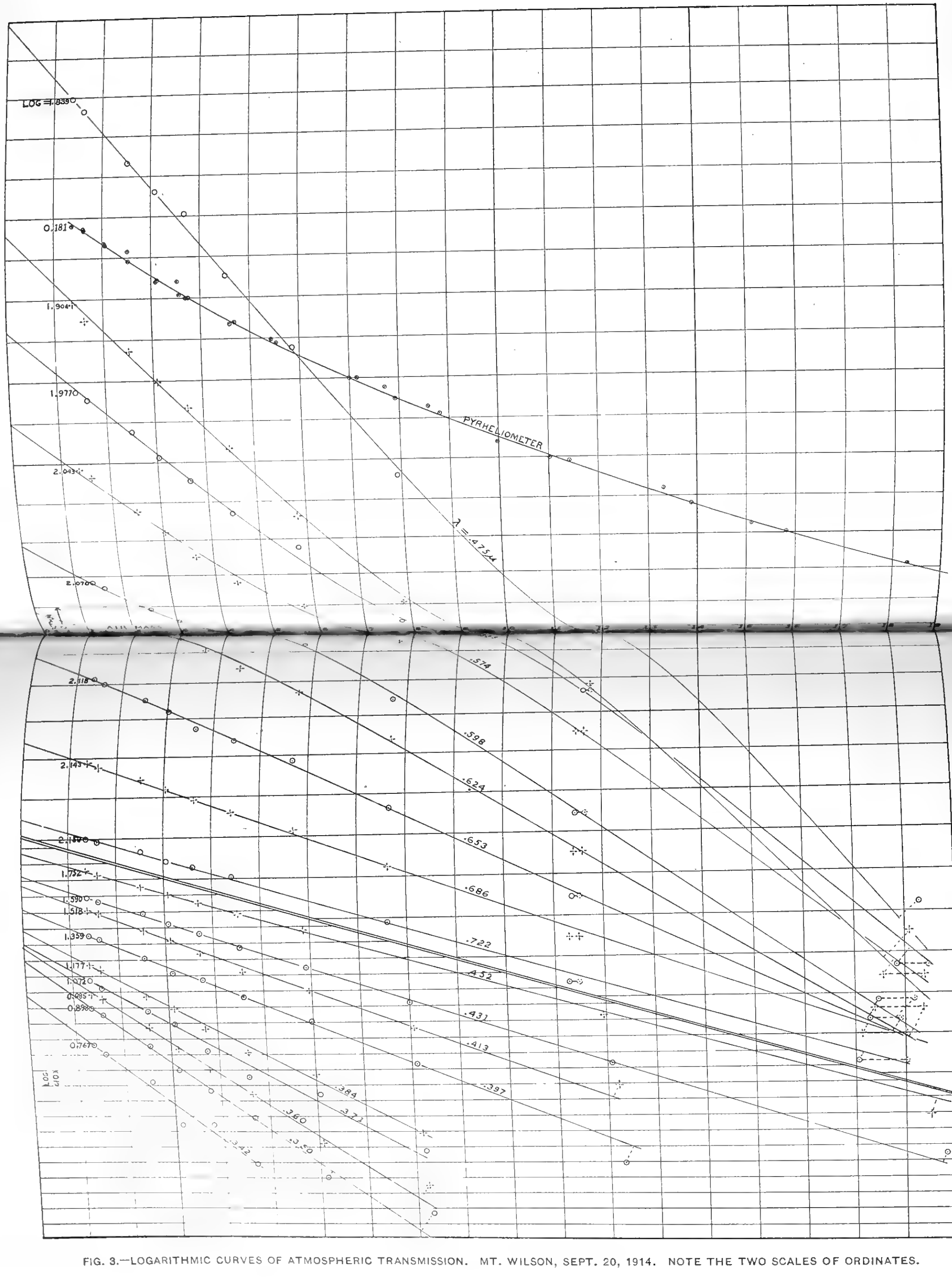


FIG. 3.—LOGARITHMIC CURVES OF ATMOSPHERIC TRANSMISSION. MT. WILSON, SEPT. 20, 1914. NOTE THE TWO SCALES OF ORDINATES.

readings of the pyrheliometer simultaneously obtained. The determination of these secondary correcting factors and of the mean bolometer constant for September 20 follows:

TABLE 9—*Sensitiveness of Bolographic Apparatus*

Bolograph	Hour Angle	Air-mass	Smooth-curve area of bolograph	Correction for ultra-violet	Correction for infra-red	Correction for water vapor and oxygen bands	Corrected area	Corresponding pyrheliometry, calories	Factor to reduce corrected areas to calories	Correcting factor in percentage	Correcting logarithm.
	h m										
I	5 53.5	17.15	7475	—	+109	—2135	5449	0.583	1.070	+7.3	.031 [1]
II	42.7	11.39	9630	—	127	2094	7663	.764	0.997	±0.0	.000
III	29.8	7.71	11129	—	132	2000	9261	.943	—	—	— [2]
IV	16.9	5.75	12436	—	138	1961	10613	1.066	1.004	+0.7	.003
V	2.0	4.46	13232	+1	136	1887	11482	1.159	1.009	+1.2	.005
VI	4 47.3	3.67	13930	25	140	1819	12276	1.233	1.003	+0.6	.003
VII	31.3	3.06	14622	41	140	1807	12996	1.294	0.996	—0.1	.000
VIII	10.0	2.53	15474	79	144	1692	14005	1.377	0.983	—1.4	.994
X	2 51.0	1.62	16576	163	150	1624	15265	1.495	0.979	—1.8	.992 [3]
XI	03.0	1.38	16317	179	144	1609	15031	1.515	1.008	+1.1	.005
								Mean	0.997		

[1] The correcting factor for bolograph I is much above the usual magnitude. It was not used for the following reasons: Firstly, the pyrheliometer exposes $\frac{1}{200}$ hemisphere, which is a sky area much larger than the sun. At ordinary air-masses the light of this area of sky is negligible compared with sunlight. But at sunrise almost ⅔ of the solar beam is lost by scattering in the sky, hence the light of the sky close to the sun is a very perceptible fraction, perhaps 5 per cent, of that of the sun itself. Secondly the radiation of the pyrheliometer to cold air and to space, which at high sun may reach nearly 0.005 calorie, is at the horizon counterbalanced by the radiation of the immense thickness of the lower and warmer parts of the atmosphere, so that in comparison with high sun observations the pyrheliometer reading at sunrise is probably about 1 per cent too high for this second cause. Exact determinations of these corrections to pyrheliometry are proposed, but not yet executed. Accordingly bolograph I was omitted in the mean of column 10.

[2] Correction could not be determined because leaves of a tree intercepted the solar beam during a part of bolograph III.

[3] Bolograph IX omitted, because shadow of a guy wire fell on the slit during a considerable part of the time.

In figures 3 and 4 we give plots to represent the results of the spectro-bolometric observations of September 20 at different wave lengths. The plots given in figures 3 and 4 are logarithmic. The ordinates correspond to logarithms of the corrected heights of the bolographs at the 38 selected points, and the abscissae of the diagrams represent the corresponding air-masses according to the tables of Bemporad, corrected as heretofore explained.

The original plots have been made on two different scales. In the first, only those observations which we would ordinarily have used for determining the solar constant of radiation were included. They were plotted on the scales of ordinates and abscissae which we customarily employ, in which, in general, 1 cm.=0.01 in logarithm, and 1 cm.=0.1 air-mass. In the other plot we have included all the

observations, using for this purpose a reduced scale of abscissae, in which 1 cm. = 0.5 air-mass.

We have read off from the plots so obtained the inclination of the best straight lines, giving logarithms of transmission coefficients; and also the intercepts on the axis of ordinates, giving logarithms of intensities outside the atmosphere. The plots were read up independently for three different ranges of air-masses. The first range is that which we customarily employ, from about 1.3 to about 4.5 air-masses. The second reading includes all points from 1.3 to 20 air-masses or thereabouts. The third reading was made with the portion of the curve which Mr. Very states to be the best, namely, from air-mass 4 to air-mass 10 or thereabouts. The results of all three readings are given in table 11. For September 20 this table gives also the percentage deviations, in ordinates, of the observed points from the natural numbers corresponding to the straight lines of the logarithmic plots which were chosen in the second reading to represent them. In order to show that the somewhat large percentage errors at some places are not inconsistent with experimental error of very moderate amount, we give for two bolographs the deviations expressed in millimeters on the original bolographs. The reader should bear in mind that the bolographic trace itself is nearly 1 millimeter wide, and subject to tremor. Also the line of zero radiation is interpolated between zero marks 1 minute of time, or 8 centimeters of plate, apart.

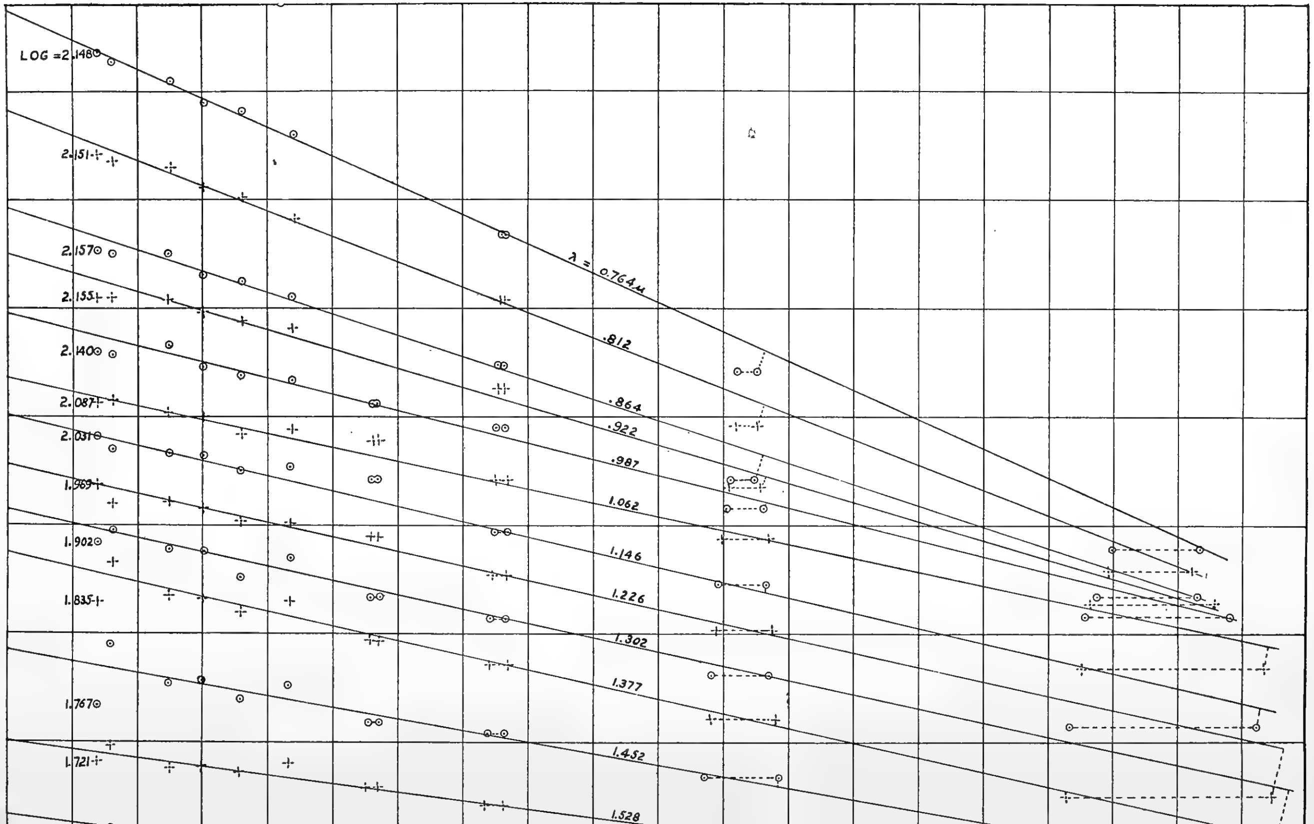
We then determined the area which the bolographic curve would include if it were taken outside the atmosphere, and we multiplied this area by the appropriate constant (see table 9) to give the result in calories per sq. cm. per minute. To this we added the small corrections to reduce the result to mean solar distance, and to zero atmospheric humidity, as explained in Annals, Vol. III, p. 43. All the details of the foregoing processes have been described and investigated in Vols. II and III of the Annals of the Astrophysical Observatory, and to these the reader is referred.

The following are the solar constant values obtained:

TABLE 10—*Solar Constant Values*

In standard calories (15°) per sq. cm. per minute at mean solar distance

Air-masses	1.3 to 4	1.3 to 20	4 to 12
Sept. 20	1.936	1.899	1.909
Sept. 21	1.960	1.955	1.929



LOG =2.148
2.151
2.157
2.155
2.140
2.087
2.031
1.969
1.902
1.835
1.767
1.721
λ = 0.764μ
.812
.864
.922
.987
1.062
1.146
1.226
1.302
1.377
1.452
1.528

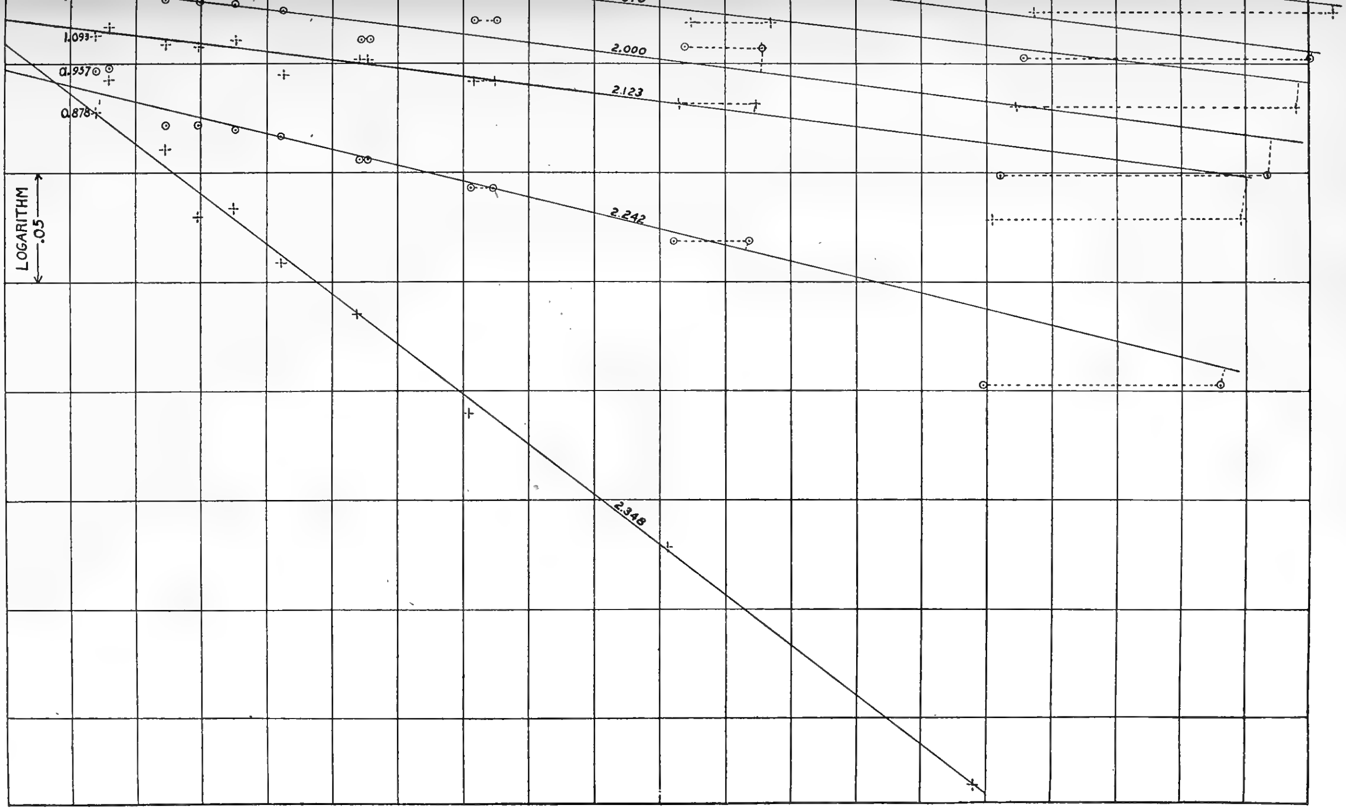


FIG. 4.—LOGARITHMIC CURVES OF ATMOSPHERIC TRANSMISSION. MT. WILSON, SEPT. 20, 1914.

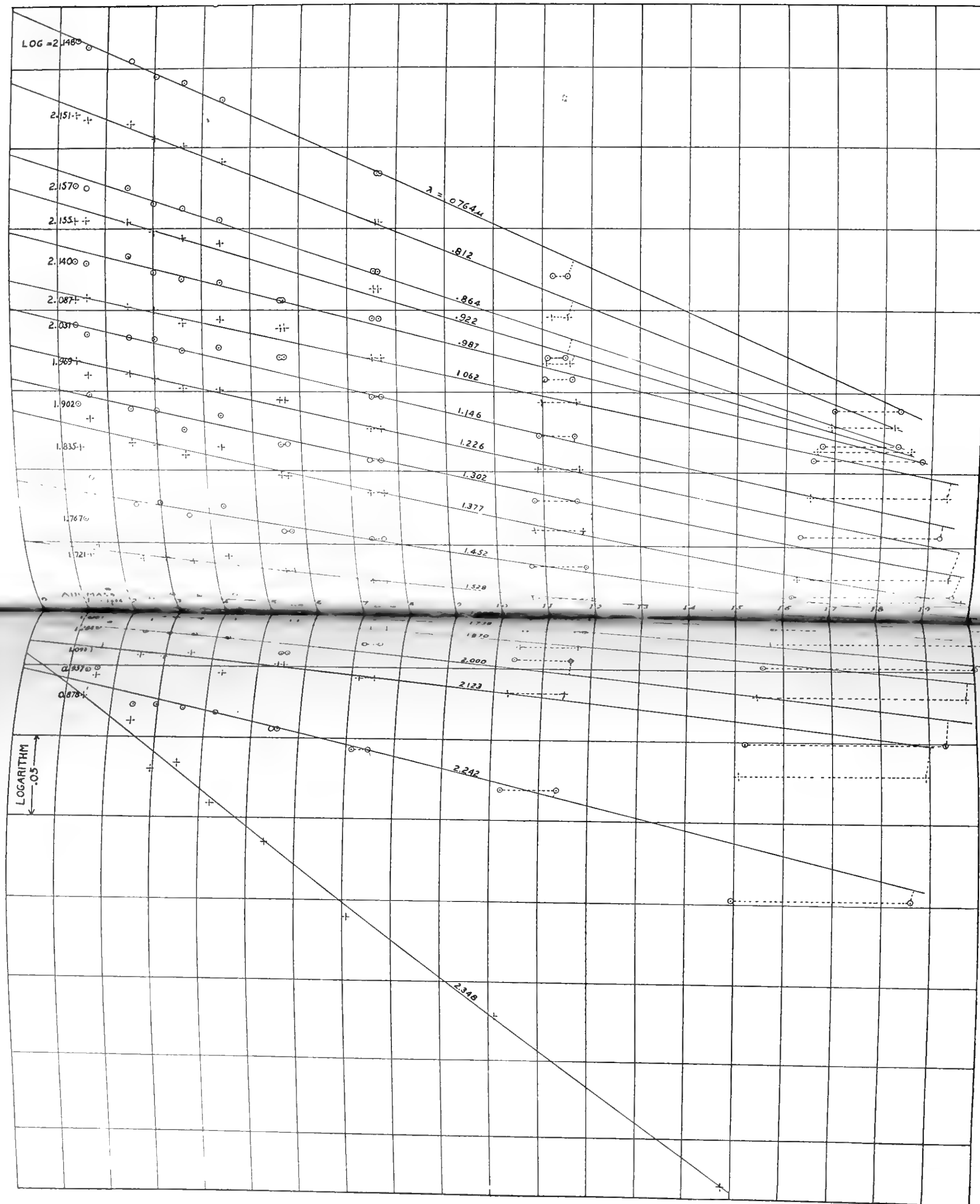


FIG. 4.—LOGARITHMIC CURVES OF ATMOSPHERIC TRANSMISSION. MT. WILSON, SEPT. 20, 1914.

TABLE II—*Atmospheric Transmission Coefficients, and Accidental Errors*

Wave length	Atmospheric transmission coefficients						Percentage deviations, Sept. 20 Computed minus observed For observed intensities found on Bolographs Nos.										Linear deviations on original bolographs in millimeters	
	Sept. 21, '14 Air-masses			Sept. 20, '14 Air-masses														
	1.3 to 4	1.3 to 20	4 to 12	1.3 to 4	1.3 to 20	4 to 12	I	II	III	IV	V	VI	VII	VIII	X	XI	I	VII
μ																		
0.342	.621	.600	.637	.615	.585	—	—	—	—	—	0.0	+10.4	−27.9	+10.4	0.0	0.0	....	1.1
0.350	.621	.575	.575	.600	.600	.637	—	—	+51.4	−14.8	+ 2.3	− 2.3	− 3.5	+ 2.3	+ 1.6	− 0.5	....	0.5
.360	.643	.625	.658	.618	.667	.652	—	—	+34.9	− 7.2	0.0	− 3.5	− 2.8	+ 2.3	+ 1.6	− 1.2	....	0.8
.371	.661	.678	.682	.681	.679	.718	—	—	+11.7	+13.5	−20.2	−12.2	+ 2.3	0.0	− 2.3	0.0	....	0.5
.384	.681	.692	.697	.681	.692	.702	—	—	+ 1.2	+10.2	+10.2	− 7.2	0.0	− 2.3	+ 2.3	+ 1.2	....	0.0
.397	.745	.731	.728	.743	.753	.753	—	−28.8	0.0	+ 3.5	0.0	+ 1.2	− 6.7	0.0	+ 1.2	0.0	....	3.3
.413	.769	.766	.766	.764	.773	.783	—	+23.0	− 1.2	− 1.2	− 8.4	− 2.3	0.0	0.0	+ 1.2	0.0	....	0.0
.431	.778	.794	.802	.794	.798	.796	−18.9	0.0	− 3.5	0.0	− 1.2	0.0	0.0	+ 4.7	0.0	0.0	0.2	0.0
.452	.841	.824	.824	.820	.820	.832	−25.9	− 4.7	− 2.3	+ 2.3	0.0	− 0.7	0.0	0.0	0.0	+ 2.3	0.7	0.0
.475	.843	.836	.836	.859	.851	.830	+12.7	− 5.0	2.6	+ 0.2	− 0.9	+ 3.3	0.0	− 0.7	0.0	0.0	0.5	0.0
.503	.879	.867	.867	.881	.873	.875	+ 5.2	+ 1.4	− 2.6	− 1.6	+ 0.5	+ 0.9	+ 0.2	+ 1.4	− 1.9	− 0.7	0.3	0.1
.535	.891	.891	.891	.893	.892	.895	− 0.5	0.0	− 1.4	+ 4.0	− 0.7	− 0.5	− 0.5	+ 0.7	− 0.5	− 0.9	0.0	0.3
.574	.897	.900	.900	.889	.903	.904	0.0	0.0	− 6.2	+ 2.3	− 2.1	− 1.2	0.0	+ 0.9	+ 1.9	+ 1.6	0.0	0.0
.598	.900	.906	.908	.904	.911	.908	+ 8.1	0.0	− 2.3	+ 0.7	− 2.3	− 0.9	0.0	+ 0.7	+ 0.9	+ 0.7	1.7	0.0
.624	.900	.918	.925	.916	.921	.920	+11.2	0.0	+ 0.7	− 0.2	− 2.1	− 1.4	0.0	+ 0.9	− 0.5	+ 0.7	3.7	0.0
.653	.931	.942	.942	.933	.936	.938	+ 1.2	− 0.5	0.0	+ 1.2	− 0.5	− 1.9	− 0.2	0.0	0.0	+ 0.5	0.5	0.2
.686	.948	.954	.953	.953	.953	.954	+ 1.2	− 1.9	0.0	+ 0.9	0.0	0.0	+ 0.2	+ 0.2	0.0	0.0	0.7	0.2
.722	.959	.961	.960	.966	.961	.960	+ 1.2	− 1.9	0.0	+ 0.7	+ 0.2	0.0	+ 0.5	− 0.2	− 0.2	− 0.2	0.8	0.6
.764	.966	.970	.971	.973	.970	.968	− 0.2	− 2.6	− 0.2	—	+ 0.5	+ 0.5	− 0.2	+ 0.5	− 0.5	− 0.2	0.2	0.3
.812	.968	.977	.979	.980	.974	.972	0.0	− 2.6	+ 0.5	—	+ 0.5	+ 0.5	0.0	+ 0.7	− 0.9	− 0.9	0.0	0.0
.864	.968	.982	.984	.982	.978	.973	0.0	− 2.8	+ 0.7	—	+ 0.7	+ 0.5	0.0	+ 0.9	− 0.9	− 0.9	0.0	0.0
.922	.975	.985	.987	.982	.980	.978	+ 0.5	− 1.2	+ 1.2	—	+ 0.9	+ 0.2	− 0.2	0.0	+ 1.4	− 1.9	0.4	0.2
.987	.984	.990	.992	.986	.983	.982	0.0	− 0.7	+ 0.9	0.0	+ 0.5	− 0.5	− 0.5	+ 0.9	− 1.4	− 1.6	0.0	0.5
1.062	.984	.990	.992	.984	.985	.984	− 2.3	0.0	+ 0.5	+ 1.9	+ 0.9	− 0.7	+ 0.5	0.0	0.0	− 0.5	1.6	0.5
1.146	.989	.990	.993	.986	.984	.983	− 2.1	+ 0.9	0.0	+ 2.3	+ 1.4	0.0	+ 0.5	0.0	− 0.9	0.0	1.3	0.4
1.226	.984	.988	.990	.989	.985	.983	− 5.7	+ 0.5	0.0	+ 1.2	+ 0.5	− 0.5	0.0	0.0	− 1.6	0.0	3.1	0.0
1.302	.980	.987	.988	.984	.985	.984	− 4.7	0.0	0.0	− 0.7	+ 1.4	− 1.6	0.0	− 0.5	+ 0.2	− 1.4	2.3	0.0
1.377	.986	.990	.990	.980	.985	.983	0.0	+ 0.7	0.0	− 0.5	+ 1.6	− 0.7	− 0.2	− 0.7	+ 1.4	− 3.0	0.0	0.1
1.452	.986	.991	.991	.977	.988	.988	− 1.4	+ 0.9	+ 0.5	− 0.7	+ 1.4	− 0.7	+ 0.5	− 0.5	+ 2.3	− 4.2	0.6	0.2
1.528	.989	.993	.992	.991	.991	.990	− 2.1	+ 0.5	0.0	+ 0.2	+ 1.6	0.0	0.0	− 0.5	+ 0.9	− 0.9	0.8	0.0
1.603	.986	.994	.994	.995	.992	.991	0.0	+ 0.2	+ 1.2	− 0.5	+ 1.4	+ 0.5	0.0	− 1.4	0.0	− 3.5	0.0	0.0
1.670	.986	.994	.994	.998	.992	.992	− 0.7	0.0	+ 1.4	− 0.7	+ 0.9	+ 0.2	+ 0.2	− 0.9	0.0	− 2.8	0.7	0.2
1.738	.989	.991	.994	.995	.992	.991	− 0.7	0.0	+ 1.4	+ 0.2	+ 0.7	0.0	0.0	− 1.2	0.0	− 3.3	0.6	0.0
1.870	.984	.991	.995	.991	.992	.990	− 2.8	− 0.2	+ 0.7	+ 0.9	+ 0.5	0.0	− 0.2	− 1.6	+ 0.5	− 1.9	1.7	0.2
2.000	.973	.992	.995	.991	.991	.994	− 3.8	+ 2.6	+ 2.6	− 1.9	+ 0.2	+ 0.2	0.0	− 0.2	+ 1.6	− 0.5	1.6	0.0
2.123	.991	.991	.992	.989	.991	.992	− 4.7	+ 1.2	0.0	+ 0.5	− 2.1	+ 0.9	− 0.2	− 0.5	+ 0.5	− 0.5	2.7	0.1
2.242	.980	.979	.986	.966	.983	.983	− 1.9	+ 1.2	0.0	− 0.2	0.0	− 0.2	− 0.9	− 1.6	+ 2.8	+ 2.3	0.5	0.3
2.348	.863	.942	.940	.925	.951	.951	0.0	0.0	− 2.1	0.0	− 0.9	+ 0.9	− 3.3	+ 1.9	+ 5.0	0.0	0.0	0.7
Means:......................							− 1.2	− 0.6	+ 2.3	+ 0.5	− 0.3	− 0.5	− 1.1	+ 0.5	+ 0.4	− 0.6	0.9	0.3

We call attention to the decided difference between the behavior of nearly homogeneous rays, as observed by the bolometer, and of the total radiation, as observed by the pyrheliometer. The logarithms of the pyrheliometer readings of September 20 are plotted against Bemporad air-masses in the upper curve of figure 3, and the reader will readily perceive the pronounced and steady change of curvature of the resulting plots. This is in sharp distinction to the close approximation to straight lines shown in the logarithmic plots of the bolometric observations at single wave lengths. Forbes, Radau, Langley, and many others have discussed this relation between total radiation and air-masses, and have shown why such

a curvature must occur in logarithmic plots of total radiation. It will be seen that our observations fully confirm their view, which depends upon the fact that the total radiation is composed of parts for which the atmosphere has very different transmission coefficients.

Referring to tables 2 and 11, and to Annals, Vol. III, table 47, the reader will see that the atmospheric transmission on September 20 and 21, 1914, was distinctly above the average, and indeed was as high as we have ever found on Mt. Wilson. Secondly, the quantity of water vapor between the station and the zenith, as found by Mr. Fowle's spectroscopic method, was unusually small and satisfactorily constant. Hence, we may conclude that the two days in question were, as they appeared to the eye, days of the highest excellence at Mt. Wilson. When we compare the results obtained from them on the solar constant of radiation, as given in table 10, with those obtained in other years, as shown in table 1 and in Annals, Vol. III, table 44, we see that the values were very close to the mean results of all our observations. We see further, from table 10, that the results obtained were very nearly the same, whether we used only the later observations, taken between air-mass 1.3 and air-mass 4, as in our usual investigations; whether we employ only the observations between air-mass 4 and air-mass 12, as recommended by Mr. Very; or, finally, whether we take all the observations from air-mass 1.3 to air-mass 20. In every case the result is the same almost within the error of computing.

From this we feel ourselves fully justified in drawing the conclusion that our former work has not been vitiated by the employment of too small air-masses, and that, in fact, hardly different results would have been obtained had we observed from sunrise of every day in which we have worked. On account of the uncertainty which attends the theory of the determination of air-masses, when zenith distances exceeding 75° are in question, we conceive that it will be better to confine our observations hereafter, as we have generally done in the past, to the range of air-masses less than 4, where the secant formula applies in all atmospheric layers, irrespective of optical density, refraction, or the earth's curvature.

Third objection.—We attach very little weight to any determinations of the solar constant of radiation which we have made hitherto, except those made by the spectro-bolometric method developed by Langley, as just employed for September 20, 1914, and which is the definitive method employed by the Astrophysical Observatory of the

Smithsonian Institution.[1] However, in Vol. II of our Annals we showed in the second part of the work that the results obtained by this method were harmonious with rougher ones obtained by considering terrestrial meteorological conditions. In the course of that discussion we used the data which were at that time available for determining the transmission through the moist atmosphere of the long-wave radiations such as the earth sends out. Mr. Very

[1] Messrs. Very and Bigelow describe as "the spectro-bolometric method" of determining the solar constant of radiation something quite different, viz.: They take our determination of the form of the solar energy curve outside the atmosphere. From this they determine the wave length of maximum energy, and from it they infer the temperature of the sun, supposing it to be a perfect radiator or "black body." They then determine the intensity of energy which a perfect radiator of the sun's size, and of the temperature which they thus decide upon, would give at the earth's mean distance. This value they regard as the solar constant.

In this determination they assume: Firstly, that our atmospheric transmission coefficients, which at other times they describe as altogether erroneous, do not distort the true form of the sun's energy curve outside the atmosphere; Secondly, that our determinations of the transmission of the optical apparatus (and these we ourselves admit to be determinations of great difficulty, and only moderate accuracy) also do not distort the form of the energy curve; Thirdly, that the position of the maximum of energy determines the proper temperature of the sun; Fourthly, that the total emission of energy of the sun is the same function of its temperature that the total emission of a "black body" is.

We are far from wishing to discredit the substantial accuracy of our determination of the form of the sun's energy curve outside the atmosphere, but we totally dissent from these authors' application of it. In the first place, the form of the energy curve as determined by us does not agree with the form of the energy curve of a "black body" at any single temperature whatever. In the second place, if the temperature of the sun could be properly inferred from the consideration of the position of maximum energy in its spectrum, even then there would be no reason to suppose that the radiation of the sun bears the same relation to its temperature as the radiation of a "black body" bears to its temperature. Since the sun is not a "black body" of uniform temperature, it may depart widely from the conditions of such a "black body."

The same method could just as reasonably be applied to the radiation of a mercury vapor lamp. The maximum of energy with such a lamp would be found in the green, as it is in the solar spectrum, and thereby, following Very and Bigelow, one could infer that the temperature of the lamp is of the order of six to seven thousand degrees absolute. Then, following still further our authors, we should assume that the mercury vapor lamp, the sun, and the "black body" at, say, 6,800° would give equal intensities of energy, provided these three sources were of equal angular size. Thus the radiation of all three would be about 3.5 calories per $cm.^2$ per min. The absurdity of this conclusion is apparent.

has confused that discussion with our definitive determination of the solar constant of radiation, of which it forms no part at all. We do not care to discuss, at the present time, the coefficients for terrestrial radiation, as we are engaged in investigations of this matter which are not as yet completed. It has no bearing upon the definitive values of the solar constant obtained by us.

As for the dependence of the transmission of solar rays upon atmospheric water vapor, we have employed the hypothesis of Langley, namely, that there will be no water vapor outside the atmosphere. This gives us the highest results which can properly be reached. As we shall see in the conclusion of this article, our results obtained in this manner are supported by another line of investigation.

Fourth objection.—We perhaps do not understand just what Mr. Very has in mind in regard to this. Certainly there is no sheet of ice or anything of a continuous surface to be found in the air, so far as we know, which would answer to the description of the conditions referred to in the fourth objection. Some approach to it may be found in the case of a cloud. But we have repeatedly ascended from Pasadena to Mt. Wilson through clouds, and even in this case we always perceived that the upper edge of the cloud had a gradual thinning out for at least many meters. We do not conceive that there is any other layer in the atmosphere for which this is not true. A transition extending through at least many meters is all that we require when we speak of a " gradual " change of transparency from one atmospheric layer to another.

As Mr. Very hints, there are irregularities in the distribution of the various bodies of air. For instance, in the neighborhood of a mountain there are currents of air of different temperatures rising and falling along the slopes. These, to be sure, do not fall into the horizontal layers postulated in our hypothesis of the atmospheric transmission, but they disturb the regular distribution in altitude so little relatively to the whole thickness of the atmosphere, and furthermore, the differences of atmospheric transmission of these different bodies of air from their immediate surroundings are so slight, that their influence on the transmission coefficients which we obtain may be neglected.

Fifth objection.—We understand that it is here claimed that the general, apparently non-selective, losses to which the solar beam is subject in passing through the atmosphere are due not only to the scattering of radiation by particles small as compared with the wave length of light as indicated by Lord Rayleigh's theory, but also to a

true absorption occurring in spectrum lines which are so fine as to have escaped discovery hitherto, although so numerous as to produce a profound effect upon the transmission of the atmosphere. Indeed, Mr. Very says in another place that one may prove that atmospheric losses in the atmosphere are at least three times as great as are indicated by Rayleigh's theory of scattering, or by the secant formula of extinction. We have found by balloon experiments, as we shall show, that the radiation at a level of about 25 kilometers, where more than twenty-four twenty-fifths of the atmosphere lies below, is still not greater than 1.9 calories per sq. cm. per minute. Hence the condition of affairs referred to by Mr. Very, if it exists, applies only to the very highest layers of the atmosphere, exerting less than one twenty-fifth part of its pressure. Apparently, however, his strongest evidence of this supposed condition of affairs is his fixed impression that the solar constant must be greater than we have found it.

As to the effect on solar radiation of particles too gross to diffract the rays, this must refer to dust particles, or agglomerations of dust and other materials about nuclei of one kind or another, perhaps about the hydrols which are thought by some to exist in the atmosphere. In regard to this we have only to refer to that line of table 2 which shows the transmission of the atmosphere for July 26, 1912, when it was filled with volcanic dust. The atmospheric transmission was then greatly reduced, but in a manner to make the sky white, not blue. Hence we may say that the particles composing the dust were large as compared with the wave length of light. But our values of the solar constant obtained both at Bassour, Algeria, and at Mt. Wilson, California, did not differ appreciably from those we had obtained in the clearest of skies.

It is urged that there are diffuse bands of atmospheric absorption which have escaped detection, but which, if taken account of, would increase the value of the solar constant of radiation. We call attention here to the results published by Mr. Fowle,[1] in which he determined in the ordinary manner, from Washington observations, transmission coefficients in the great infra-red water vapor bands. These transmission coefficients, as he showed, sufficed almost, or quite, to obliterate these bands from the energy curve of the sun outside of the earth's atmosphere, just as they ought to do, if effective, seeing that no water vapor exists in the sun. If, now, there are other bands which are so inconspicuous that they cannot be found

[1] Smithsonian Misc. Coll., Vol. 47.

without the most careful consideration of the atmospheric transmission coefficients, as indeed Mr. Fowle's researches on the relations of the transmission coefficients to Lord Rayleigh's theory of the sky light have shown, still their effects will be eliminated in the same manner as the infra-red bands were in the investigation just cited, because the transmission coefficients in such spectrum regions will be smaller than they would have been had the bands not been present there. We feel satisfied that the existence of such bands, even if there are any others than those which we know of, would hardly in the slightest degree influence the value of the solar constant of radiation.

Sixth objection.—In regard to this matter, we think Mr. Very has misinterpreted our procedure. We did not determine the quantity of energy contained in the extreme infra-red part of the emission of a "black body," of the size and distance of the sun, at 6,000° absolute temperature, and add that to what we have found from our spectro-bolometric observations. On the contrary, our procedure has been to piece out the spectro-bolometric curve as we have found it to be outside the atmosphere, by joining onto it, where our determination ends, a curve after the form of the distribution of energy computed by the Wien-Planck formula for the "black body" at 6,000°. If, now, the condition of the sun is such that its distribution of radiation in the infra-red corresponds to a "black body" at 7,000°, or some still higher temperature, then the real rate of the falling off of the curve in the infra-red, beyond the region that we observe, would be *more rapid* than that which we have assumed it to be. Accordingly the area included under such a curve would be *less* than we have assumed it to be, and thus our value of the solar constant of radiation will be *too large* on account of the error of our method of extrapolating in the extreme infra-red, rather than too small, as Mr. Very maintains. At all events, surely the difference so far down in the spectrum as this is altogether trifling in amount.

Seventh objection.—We agree with Mr. Kron that the ultra-violet spectrum may be a little more intense than we have supposed it to be. However, when we consider the rapid falling off of solar energy in the violet, and the reasonableness of it in view of the immense number of solar absorption lines and other solar circumstances, we see no probability at all that the part neglected would exceed 1 or 2 per cent, at most, of the value of the solar constant of radiation. In confirmation of this view, we point to the results of the balloon flights, which we shall shortly describe.

Eighth objection.—As Mr. Very, in a recent article, has shown that Mr. Bigelow's thermodynamic considerations are erroneous, it is not necessary to discuss them further.

SOUNDING BALLOON OBSERVATIONS

Now we come to the final piece of experimental evidence which we have secured, which seems to us to show that our solar constant results are undoubtedly very close to the true ones, and that if there be any circumstances which have led to the underestimation of the losses which the solar beam suffers in the atmosphere, they at any rate relate to the part of the atmosphere which lies beyond the altitude of 24 kilometers, and where the total pressure of it is less than one twenty-fifth of that which prevails at sea level.

In January, 1913, it was determined on the part of the Smithsonian Institution to support an expedition to California, in charge of Mr. A. K. Ångström, for the purpose of observing the nocturnal radiation at various altitudes. In connection with this work, the Institution invited the cooperation of the United States Weather Bureau for the purpose of sending up sounding balloons and captive balloons, in order to determine the humidity and temperature at various heights in the atmosphere, at the time of Mr. Ångström's experiments. While discussing the proposed expedition with Mr. Ångström, he inquired of us whether it might not be possible that an instrument could be devised for measuring the intensity of the radiation of the sun at the highest altitudes to be reached by sounding balloons. After due consideration of the matter, it was deemed by us feasible to do this.

Accordingly in the months of April, May, and June, 1913, there were constructed at the instrument shop of the Astrophysical Observatory, five copies of a special recording pyrheliometer, modified in form from the silver disk pyrheliometer which we ordinarily employ in solar-constant work.

The five instruments were sent up, in cooperation with the U. S. Weather Bureau, by Mr. Aldrich, at Avalon, Santa Catalina Island, California, in July and August, 1913. All were recovered, and all had readable records of more or less value. In these experiments, the balloon in one instance reached the height of 33,000 meters, but unfortunately, owing to the freezing of the mercury contained in the thermometers, the pyrheliometric records did not extend above an altitude of 14,000 meters in any case. There were, besides, certain sources of error which had not been anticipated at that time, so that the results of the expedition could only be regarded as of a prelimi-

nary character. The results, such as they are, indicate radiation values not exceeding 1.8 calories per cm.^{2} per min.

Early in the year 1914, we began to rebuild the instruments, which had been injured in their flights. On February 18, the preparations having been considerably advanced, Mr. Abbot wrote the following letter to Mr. Very, which is self-explanatory:

FEBRUARY 18, 1914.

Dear Mr. Very:

As you know, we are interested in the value of the solar constant of radiation. We know that you are also. In our view this quantity lies between 1.9 and 2.0 calories per sq. cm. per min. In yours it lies between 3.0 and 4.0 calories or possibly higher. All measurements made by us rest on the "Smithsonian Revised Pyrheliometry of 1913." They are 3.5 per cent higher than they would be on Ångström's scale, as shown by numerous comparisons made in America and Europe. In the interests of ascertaining the truth, which I know to be your sole object, as it is ours, will you be so good as to answer these questions:

1. Do you consider the "Smithsonian Revised Pyrheliometry of 1913" as satisfactorily furnishing the standard scale of radiation?

2. If not, why not?

3. If in error, is it too high or too low, and how much?

I assume that you are not likely to think its results as much as 5 per cent too *low,* and that the discrepancy between your ideas of the solar constant and ours lies mainly outside of our conclusions as to the realization of the standard scale of radiation. In this posture of affairs, I propose to try the following experiments, which I hope will be crucial:

By cooperation with the United States Weather Bureau we propose to send up with balloons five automatic-registering pyrheliometers in June or July next. In preliminary experiments last summer the balloons generally reached 20 to 30 kilometers altitude, and in one case 33 kilometers. Mr. Blair expects personally to attend to the balloons this year, and hopes to get them all above 30 kilometers, and some even to 40 kilometers. [This hope was disappointed, probably because the balloons used in 1914 were a year old.] These elevations are of course *derived* from barograph records, and it is not the *elevation* we care about, but the *pressure of atmosphere above.* This is given directly by the barographs, which will be calibrated, at the temperatures expected, by Mr. Blair. [Calibrations were finally made at the Smithsonian Institution.] We may expect the pressure reached will be less than 1 per cent of that at sea level. It is designed to make the pressure record on the same drum as the pyrheliometer record, so that there can be no error by differences of running of independent clocks.

I now come to a second group of questions.

4. Do you think that the intensity of the solar radiation in free space at the earth's solar distance is materially higher than that at a station within the atmosphere of the earth, where the barometric pressure is less than 1 per cent of that which prevails at sea level?

5. If so, how much and why?

I assume that you do not think the radiation in free space would be as much as 5 per cent the higher of the two. If so, the proposed balloon experiments may be expected to be conclusive to you as well as to me, if you are satisfied as to their accuracy.

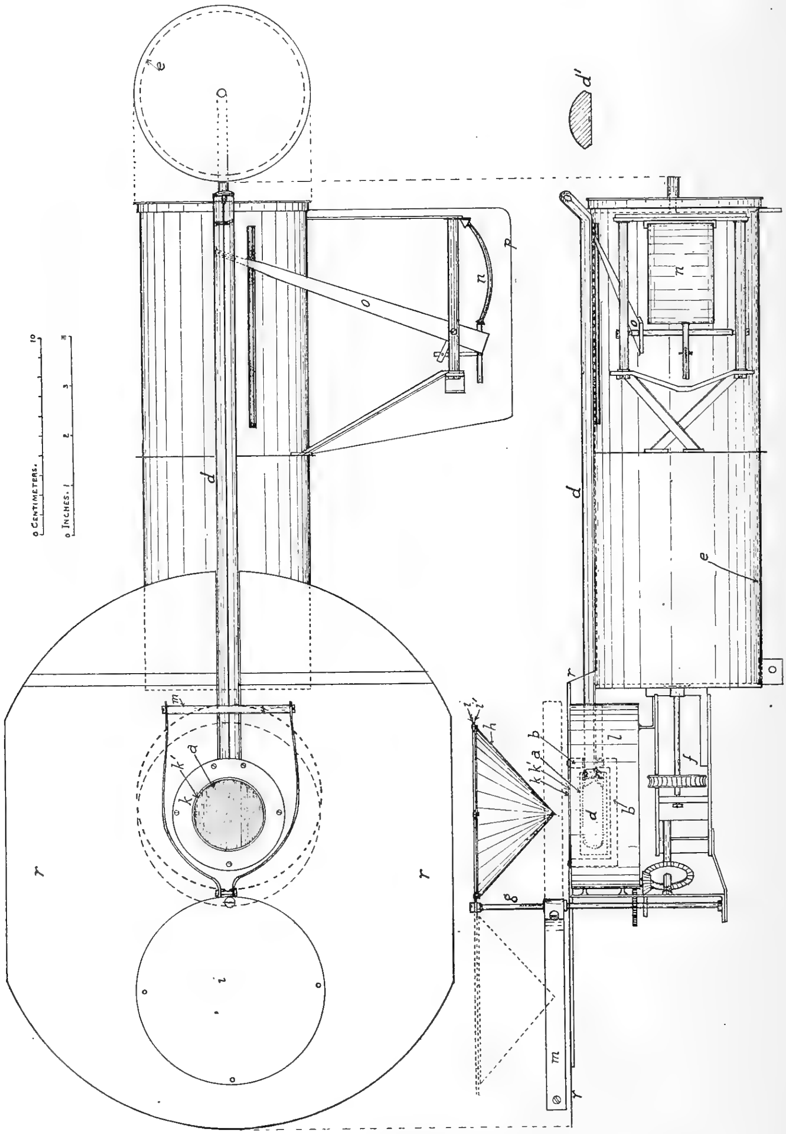


FIG. 5.—Balloon Pyrheliometer.

The apparatus is now in so forward a state of preparation that if you should be in Washington I hope you will do me the kindness to come and see it and discuss it. As that may be impracticable, I give the following details which

may enable you to suggest sources of error which may be removed before the flights take place, or at least satisfactorily determined in advance by experiments.

This instrument is a modified form of our disk pyrheliometer. A blackened aluminum disk, *a* (fig. 5), encloses a thermometer, *d*, whose stem is shown in enlarged cross section at d^1. The cavity for the bulb of the thermometer within the disk, *a*, is filled up with mercury, and sealed at the mouth with thread and wax as in our pyrheliometers. The disk is enclosed in an interiorly blackened aluminum box, *b*. Two polished copper rings, k k^1, limit the solar beam to a cross section less than that of *a*. As the temperature of the disk *a* changes, the mercury in the stem fluctuates, thus allowing the sun to print on more or less of the length of the photographic drum, *e*, according to the temperature. Thus when the paper (solio paper) is removed, there is a record like this (see fig. 9):

A clock work *f* rotates the drum, and at the same time causes the shutter, g h i i^1, to be for four minutes in the position above the disk *a* as shown, then four minutes opened (as partially shown dotted at the left), then again closed as shown, and so on, rotating, at the end of each four minutes, 180° on *g* as an axis. The shutter comprises three parts. Of these *i* and i^1 are polished aluminum disks, and *h* a polished silver cone. The angle of the cone, *h*, is such that all rays from *a* must go either directly or by reflection to the sky, none to the earth. Hence when the shutter is closed the disk *a* observes the sky directly, or by reflection, though not the zenith sky. When the shutter is open the disk observes the sun plus the sky, at this time the zenith sky. Hence the difference between the radiation exchange when the shutter is open, or closed, is not entirely due to the sun, but in part to the difference between zenith and horizon sky, and to the imperfect reflection of silver. These differences are, however, not large, and they may be approximately determined. At high levels the skylight will diminish, and the difference of radiation exchange to surroundings (other than the sun) between shutter open and shutter closed may become very small indeed, compared to solar radiation. The shutter is made, when closed, to hide the sky to 30° zenith distance from all parts of the disk *a*, when the apparatus hangs as if suspended from the balloons. The apparatus is hung by a steel wire of nearly 25 meters length below the balloons.

In order to prevent the mercury in the thermometer from freezing, the cup *b* is wound outside and underneath with resistance wire, and batteries are taken along to heat the wire. Their action is automatically controlled by a curved strip of brass and invar *c* lying in a groove in the cup *b* and arranged to open against platinum points and complete circuit when the temperature of the curved strip goes below 0° C. [This arrangement was not used in the most successful flight, and is not shown in fig. 5.] The whole apparatus is covered with a blanket of black silk and down, excepting the top of the disk *a*, the shutter *h*, and the thermometer stem *d*.

Each instrument is to be repeatedly calibrated against silver disk pyrheliometers before sending it up, and the flights are to be made on cloudless days, and pyrheliometer readings taken on the ground during flight. A correction to the aperture for zenith distance of the sun will be made.

As stated above, similar experiments have already been made with considerable success in 1913. Records to 13,000 meters were obtained, but for lack of the heating apparatus above mentioned the mercury froze, and prevented

higher records. Since then the apparatus has been wholly rebuilt, with Richard clocks, and the best possible driving mechanism, so that backlash of the drum is nearly eliminated.

Neither you nor I have read, or ever can read, the pyrheliometer outside the atmosphere. It is now proposed to cause automatic pyrheliometers to observe as high up as possible. In the interest of learning the truth I beg that you will be so good as to suggest to me wherein the proposed experiments are likely to fail, so that all possible precautions may be taken against failure. Undoubtedly it will be impossible to get results to 1 per cent, but—

6. Do you see any reason why the experiments should not be decisive as between a solar constant of 1.9—2.0 calories and one of 3.0—4.0 calories?

I await with much interest your replies to my six (6) questions, and any suggestions you may have the goodness to offer.

In response to this communication, Mr. Very was kind enough to send two letters which contain very valuable suggestions. We quote a portion of the letters as received.

(a) Without actually experimenting myself with such actinometric apparatus as you use, I should not care to express an opinion as to its efficiency.

(b) I regard the upper isothermal layer of the atmosphere as due mainly to local heating through absorption of solar radiation. Until we get above that layer, I should expect to find increment of solar radiation with each increase of altitude. It seems to me improbable that this limit will be reached at 40 kilometers.

(c) Any plan for a high level measurement of solar radiation which has even a small prospect of success may be worth trying. It is to be regretted that yours involves the local application of electric heating, which seems to me very risky and liable to produce all sorts of complications and unforeseen results. . . . I would suggest that ascension should be made at night with a little electric lamp to give the record, to see what sort of a record you would get when the sun is away. The combination of night and day records might enable you to eliminate some errors inevitable in the method. . . . If your disk and its attachments are too massive four minutes exposure may not be long enough. You cannot use a very long exposure because the balloon ascension ends too soon. It behooves you therefore to have your thermometer and disk made on the smallest possible scale. Another thing which may be unavoidable in your construction is the very circumscribed protecting case. The same instrument may read differently in a wide, roomy case. . . . The knowledge of how such an apparatus as you are proposing will behave in the absence of the sun seems to me almost indispensable. Thus I should be apprehensive that the interpositions of the metal cone above the heat-measuring disk will act as a wind shield to some extent. There will, therefore, be less cooling from contact with the air during shade that there would be if the wind effect were constant, and the fall of temperature in shade will be too small in the day observation. At night there might even be a rise of temperature when the cone is interposed, and it is desirable to learn whether this is so, and the amount of the change. . . . During the most rapid part of the ascent, the instrument is exposed to a strong resultant air current, which may exceed 7 meters per second. This powerful wind blowing directly upon the face of the

instrument must tend to keep it at air temperature, and will diminish the effect of the sun's rays. During calibration, steady, artificial, vertical air currents, of 1 to 10 meters per second, should be made to impinge upon the face of the instrument, and the results tabulated in comparison with the record of a standard instrument, not thus affected. It is partly on account of this strong downward air current that I do not approve of your shallow cup, because this construction allows nearly free access of air currents to the heated surface, which is liable to work great harm to the observations unless corrections are determined from elaborate researches. . . . I like the principle of the Violle actinometer, namely, that of a wide, encompassing jacket at constant temperature; and although some sort of a compromise must be made in your case, it might be better to use a broader disk (even though this diminishes the sensitiveness of the arrangement) and to place this disk at the center of a double-walled alcohol jacket several inches in diameter. This will surely diminish the wind effect, although I should still want to calibrate the thing with the same strong downward currents as noted above. . . . By rights the temperature of the alcohol jacket should be recorded, as in Violle's instrument. This would require another thermometer, and a duplicate registering apparatus. With an alcohol jacket the mercury thermometer would work down to nearly —40° centigrade, and, with the greater protection of a circumscribed aperture and partial shielding from the wind, I should suppose that the apparatus might continue to register when the outside air is quite a little colder than this. But here I am only guessing, and there is the same objection to doing that in the present case as there is to answering your "six questions." I prefer to leave the guessing to you, and only say: Try it! And I wish you success.

In view of Mr. Very's excellent suggestions, four of the instruments were arranged to be used by day, and one, with a row of electric lights above the thermometer for recording purposes, was arranged to be sent up at night. In two of the day instruments the proposed electric heating was dispensed with. In place of it, there was substituted a chamber of water (*l*, fig. 5), completely enclosing the sides and bottom of the aluminum cup, within which is placed the aluminum disk. A large number of copper strips for conducting heat were disposed in all directions through the water chamber, and soldered to the inside wall of it, so as to bring the water in intimate thermal conductivity with the immediate surroundings of the aluminum disk. Thus it was hoped to make use of the latent heat of freezing of the water, so that, in fact, the water jacket would act as a constant temperature case, to prevent the cooling of the thermometer below the freezing point of water. This worked excellently.

A change was made from the practice of 1913 in attaching the barometric element as a part of the pyrheliometer, instead of sending up a separate meteorograph. Barometric elements, loaned by the Weather Bureau, were mounted as shown at *n*, figure 5. The light aluminum arm, *o*, passing through a slot in the side of the cover

cylinder, rests upon the photographic paper on the drum, *e,* between the thermometer, *d,* and the drum. A little longitudinal slot is cut in the aluminum arm, *o,* at the point where it passes under the thermometer, so that, as the drum revolves, the sun prints through the thermometer stem and the slot, and makes a trace of the position of the arm, *o,* appearing as a dark narrow streak between two light streaks.

No temperature record was obtained in the pyrheliometer flights of 1914. Certain corrections to the barometric readings depending on the temperature were worked up by a consideration of the temperatures found in other flights, as will appear in its place. It would have been better if the mounting of the barometric element had been wholly of invar, so as to reduce these corrections, but no essential harm seems to have resulted.

The size of the apparatus was made as small as seemed practicable, and its entire weight, including about one-half pound of water but exclusive of silk, feathers, and cotton used for wrapping, was only three pounds for the water jacketed instruments. The electrically heated instruments, with their battery [1] and devices for operating it, weighed about four pounds.

METHOD OF READING PYRHELIOMETER RECORDS

The records indicate the rate of rise of temperature of the aluminum disk during exposure of it to the sun, and the rate of fall of temperature of it during shading. One desires to know the rate of rise during exposure as it would be if there were no cooling due to the surroundings. In reading a record, it was fastened upon a large sheet of cross-section paper, with the degree marks of the balloon pyrheliometer record lying parallel to the section lines, in abscissae. A fine wire was then stretched parallel to a branch of the zigzag trace, and the tangent of its inclination to the degree marks was read upon the cross-section paper. Each such tangent was determined by several readings. The tangent representing each solar heating was then corrected by adding to it the mean value derived from the coolings preceding and following it. Thus we obtained, in arbitrary units, values proportional to the solar heatings. The same method of reading was applied to the records obtained while calibrating the balloon pyrheliometer, at Omaha, and at Washington, before and

[1] A special form of Roberts cell was developed, comprising tin, nitric acid, and carbon. Each cell was of 20 grams weight, 1.3 volts potential, and furnished an average of 0.4 ampere for 2 hours.

after the flight, against standardized pyrheliometers, and so the results were reduced to calories per sq. cm. per minute.

SOURCES OF ERROR

1. EFFECT OF AIR CURRENTS

In relation to the important point raised by Mr. Very regarding the effect of a downward current of air, a balloon pyrheliometer was calibrated in a current of air. The method of doing this is shown in figure 6, in which *a b* represents a 20-inch pipe connected to the

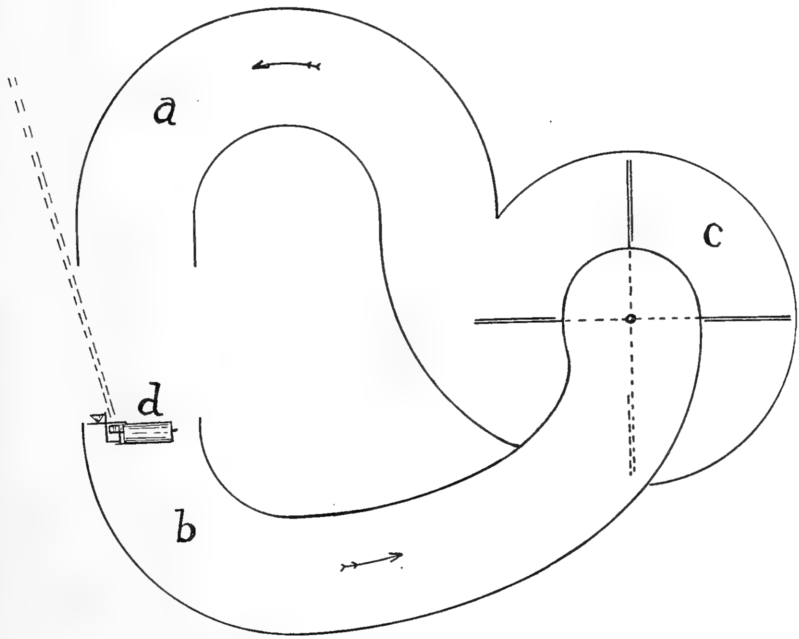


FIG. 6.—Testing the Balloon Pyrheliometer in Air Currents.

blower *c*, and causing the current of air of known velocity to pass over the balloon pryheliometer *d*. In this situation the balloon pyrheliometer was compared, with and without flow of air, with the standardized silver-disk pyrheliometer. The rate of flow of the air was taken at 5 meters per second, which would be the maximum rate of ascent of the balloon during its flight.

The results of these experiments were surprising to us, for we had assumed, with Mr. Very, that the effect of the downward current of air would be to increase the rate of cooling of the aluminum disk when the shutter was *open*. The contrary appears to be the case, for

the corrected readings of the balloon pyrheliometer were, at the first, about 16 per cent higher when the current of air was in operation than when read in still air.

We reduced this source of error very greatly, by attaching to the instrument a flat plate of blackened tin (*r*, fig. 5), level with the copper ring diaphragms which admit the light to the aluminum disk, and extending out from the copper disk to about 25 centimeters in diameter. This tin plate deflected the current of air in such a manner that the magnitude of the error we had found became reduced to 4 per cent. It seemed to us that the error must be proportional to the number of molecules carried down by the current of air, and that it would therefore decrease directly in proportion to the pressure of air in which the instrument found itself. Accordingly we believe that at the altitude reached by the instrument, namely, 24 kilometers, where the pressure of the air is only one twenty-fifth of that which prevails at sea level, the effect of this source of error will be to increase the reading of the pyrheliometer by only about 0.2 per cent.

2. VARIATIONS IN SKY EXPOSURE

As indicated in Mr. Abbot's letter, there was expected a difference in the radiation exchanged by the instrument with the sky, depending upon whether the shutter is opened or closed. This difference grows less and less as the instrument goes to higher and higher altitudes, but there could readily be a source of error here if the instrument were compared on the ground with another instrument exposing the disk very differently.

To avoid this source of error, one of our older pyrheliometers, No. V, was reconstructed, so that it might be exposed to the sun and sky in exactly the same manner as the balloon pyrheliometer. In fact, one of the balloon pyrheliometers was taken to pieces, and the copper diaphragms and the shutter were transferred to pyrheliometer No. V, so that, in respect to its exposure, pyrheliometer No. V became identically similar to the balloon pyrheliometer No. 3. The two instruments were then compared, and the result of the 16 determinations gave us the ratio of their readings: $\frac{\text{No. 3}}{\text{No. V}} = 1.882 \pm 0.024$. We then returned pyrheliometer No. V to its original condition, except that we retained the same copper diaphragms, so as to prevent any error from the measurement of the size of the aperture; and we compared it with silver disk pyrheliometer No. 9. By 14 comparisons we determined the constant of pyrheliometer No. V in these

circumstances to be 0.849 ± 0.003, to reduce its readings to calories per cm.[2] per minute. From this we find the constant of balloon pyrheliometer No. 3 to be 0.451 ± 0.006.

In this way, it appears to us, the source of error above mentioned was avoided. A few comparisons were also made at Omaha directly between balloon pyrheliometer No. 3 and silver-disk pyrheliometer No. 9. These show the magnitude of this error, for assuming that no such error as above considered exists, the results of these comparisons yield for the pyrheliometer No. 3 the constant 0.414, which differs by 8 per cent from the value obtained by the preferred process.

3. ROTATION OF THE INSTRUMENT

Another source of error which was not inconsiderable depended upon the rotation of the balloon during its flight, for the instrument not only rotated, but swung around a small cone, so that the average angle made by the sun rays with the surface of the aluminum disk was not given immediately by a knowledge of the latitude of Omaha and the declination and hour angle of the sun at the time of exposure. Fortunately the record of the flight gave means of determining this small correction. The record of the degrees marked upon the thermometer stem, instead of being a series of parallel fine lines as they are shown in figure 9, became broadened out as the instrument rotated. By measuring the distance apart of the edges of the broadened lines, as compared with results found in check experiments made by moving the instrument through known angles, the half angle of the cone during the highest part of the flight was determined and found to be about 9 degrees. It was then computed that a correction of about 1.2 per cent should be added to the readings over and above that of about 8 per cent which was due to the zenith distance of the sun.

4. RATE OF THE CLOCKWORK

At Omaha, on July 2, 1914, during calibrations, the mean period occupied by a complete rotation of the shutter was found $8^m\ 17^s$; at Washington, on December 26, 1914, during calibration, $8^m\ 18^s$. Other records give similar indications of substantial constancy of rate of the clockwork. However, on February 4, 1915, at $+19°$ C., the mean rate of the drum was .02154 mm. per sec., while at $-46°$ C., the mean rate found was .0217 mm. per sec. This indicates a change of 1 per cent for the range of temperature $+34°$ to $-37°$, which occurred on July 11, 1914. This error would tend to diminish the results by 1 per cent.

5. HORIZONTAL THERMOMETER STEM AND CALIBRATION

A difficulty was encountered in the experiments of 1913, for, owing to the horizontal position of the thermometer stem, the mercury thread sometimes separated, and failed to return after a rise of temperature. This was overcome by drilling a hole into the upper bulb, just before the flight, so that air pressure came upon the mercury column. In 1913, this worked perfectly satisfactorily, but in 1914 the mercury column became foul in every case but that of No. 5 pyrheliometer, owing probably to the creep of the lubricant used in drilling the glass. This prevented the use of pyrheliometers Nos. 1 and 2, and required several washings with benzol and alcohol before the bore of Nos. 3 and 4 was clean enough to be used. Even then the upper temperatures were unavailable, so that no use could be made of records at low altitudes in the flights of July 9 and July 11, 1914.

The reader will perhaps wonder why there was not left a small gas pressure above the mercury column in the original construction. This was not done, for we were required to calibrate the thermometer stems because their bores were not uniform. We could most readily do so by breaking the mercury thread and moving a short column from place to place in the bore, observing its length-changes. This we did for all the thermometers, and have corrected our results accordingly. In view of our experience we should now prefer to introduce gas pressure in the original construction, and calibrate the thermometers in baths of known temperatures.

6. OTHER CORRECTIONS

The aluminum disk, during the highest flight, differed slightly in its mean temperature from that which it had during calibration. Owing to change in the specific heat of aluminum with change of temperature, a correction of 0.5 per cent should be deducted for this.

The suspending wires in their rotation shaded the disk. A correction of 0.2 per cent should be added for this.

Variations in the absorption of the disk by deterioration of the blackened surface between July and December are thought to require a correction of somewhat less than 1 per cent to be deducted.

Variations in reflecting power of the copper diaphragms used in the calibrations are thought to require an additive correction of 0.25 per cent.

While the effect of the downward current of air seems to be nearly negligible, as indicated above, it may be possible that the considerable difference of temperature between the disk and the air during recording at highest altitudes tended to alter or change the sign of this error.

In consideration of all circumstances, it seems to us that the various small positive corrections, including the error below mentioned in determining the angle of the cone of rotation, but not that for clock rate or for inclination, may be regarded as balancing the various small negative corrections. We consider, therefore, in what follows, only the direct results of the exposures, the calibration at Washington, the correction for effective solar zenith distance, the correction to mean solar distance, the correction for clock rate, and the probable correction to reduce to outside the atmosphere.

CIRCUMSTANCES OF OBSERVATION

The following circumstances attended the balloon pyrheliometer flights at Omaha: Observers: For the Smithsonian Institution, L. B. Aldrich; for the U. S. Weather Bureau, Dr. Wm. R. Blair, B. J. Sherry, and Mr. Morris.

India rubber balloons, imported by the Smithsonian Institution from Russia in July, 1913, were used. They were 1.25 meters in diameter, inflated with hydrogen gas, and were sent up in groups of three attached as shown in figure 7.

It was expected that after two of the balloons had burst by expansion, at high altitudes, the third would bring down the apparatus in safety. A reward was offered for the safe return of the apparatus by the finder.

In addition to the barometric element, as a means of measuring heights reached, the balloons were observed by two theodolites, separated by a known base line.

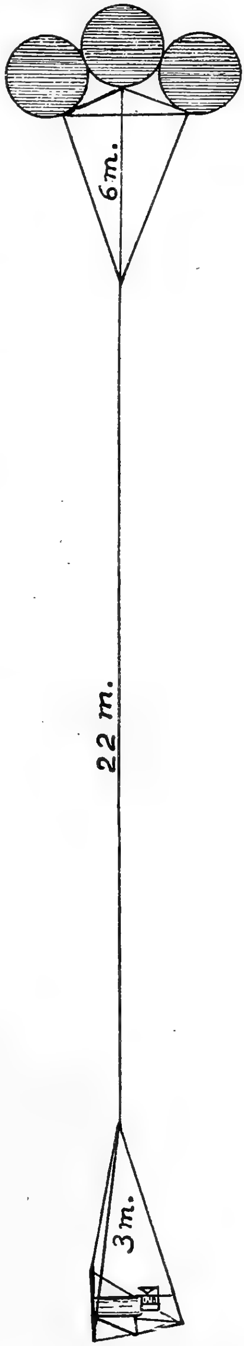


FIG. 7.—Method of Suspending Balloon Pyrheliometer.

JULY 1, 1914. NIGHT ASCENSION

Balloon launched with No. 5 pyrheliometer at $11^h\ 26^m$ p. m. in clear sky. Moon half full and setting. Wire, 22 meters long, plus 3 meters, plus 2 meters. Total, 27 meters. Electric flash light attached, but could be followed only a few minutes with theodolite at Fort Omaha, and was not seen from the second station. The apparatus was found July 3, 6.30 a. m., at Harvard, Iowa, two balloons still inflated. The instrument was somewhat damaged, but the record not harmed.

JULY 9, 1914

Balloon launched with No. 4 pyrheliometer at $10^h\ 8^m$ a. m. Balloons followed by theodolites at both stations for $1^h\ 5^m$, and at one station for $2^h\ 16^m$. One balloon burst after 42^m, another after $2^h\ 4^m$. The apparatus was found at Omaha after 20 days, but the record was spoiled by light and water, and the instrument greatly damaged.

JULY 11, 1914

Balloon launched with No. 3 pyrheliometer at $10^h\ 30^m$ a. m. Sky fairly clear, save for cirri near the horizon. All clear near the sun. Balloons followed by theodolites at both stations for 35 minutes, and at one station for over two hours. Two balloons burst nearly simultaneously, after $1^h\ 47^m$. Pyrheliometer A. P. O. 9 was read immediately after the launching as follows: At $10^h\ 35^m$, 1.147 cal.; at $10^h\ 39^m$, 1.161 cal. Apparatus found 3½ miles northwest of Carson, Iowa, on July 11, at 5 p. m., and received entirely uninjured at Mt. Wilson, California. It was later carried uninjured to Washington, and tested in various ways during the following winter.

Weights of apparatus and accessories:

	Grams
Three balloons, at 2,880 grams each	8,640
Pyrheliometer	1,250
Water in jacket	170
Silk, feathers, and cotton wrapping	370
Wire	50
Total	10,480

DISCUSSION OF RECORDS

I. THE NIGHT RECORD

In figure 8 is given a reproduction of the record obtained in the night flight made at Omaha on July 1, 1914. $A_1\ A_2\ A_3\ A_4$ is the barometric record, $B_1\ B_2\ B_3$ the pyrheliometer record. As shown,

the lighting current was cut off intermittently to prevent premature exhaustion of the battery. Unfortunately the mechanism failed to make electrical contacts in the region A_2 A_3, so that the pyrheliometer

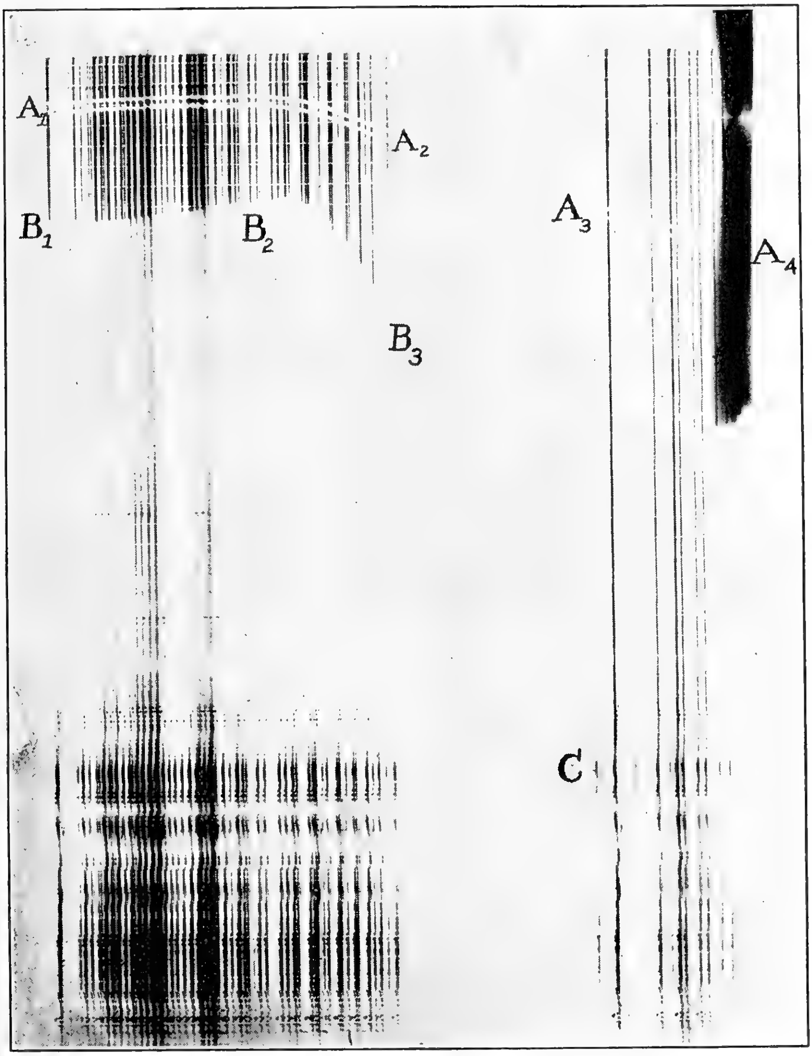


FIG. 8.—Night Record with Balloon Pyrheliometer.

record is missing there. It does not show in the last part of the record corresponding to A_3 A_4, from which we infer that the electrical heating proved insufficient to hold the temperature of the disk above about —15°, corresponding to the position C, and that the record

is lost in stray light somewhere below C. But from B_2 to B_3 is a period of 20 minutes, during which there were 2½ complete rotations (5 swings) of the shutter, and the apparatus rose about 3,000 meters.

Apart from the slight fall of temperature shown at B_2, when the instrument was removed from the balloon shed, there is no appreciable sudden change of temperature, but only the gradual march attending increasing altitude. No periodic change attributable to the opening and closing of the shutter is discernible. From this we conclude that no considerable error is caused by the current of air due to the uprush of the balloons, which it was thought might cool the disk unequally, depending on whether the shutter is open or not.

2. THE DAY RECORD

The record obtained in the day flight of July 11, 1914, was on solio paper. It was read up while still unfixed, and was at that time very

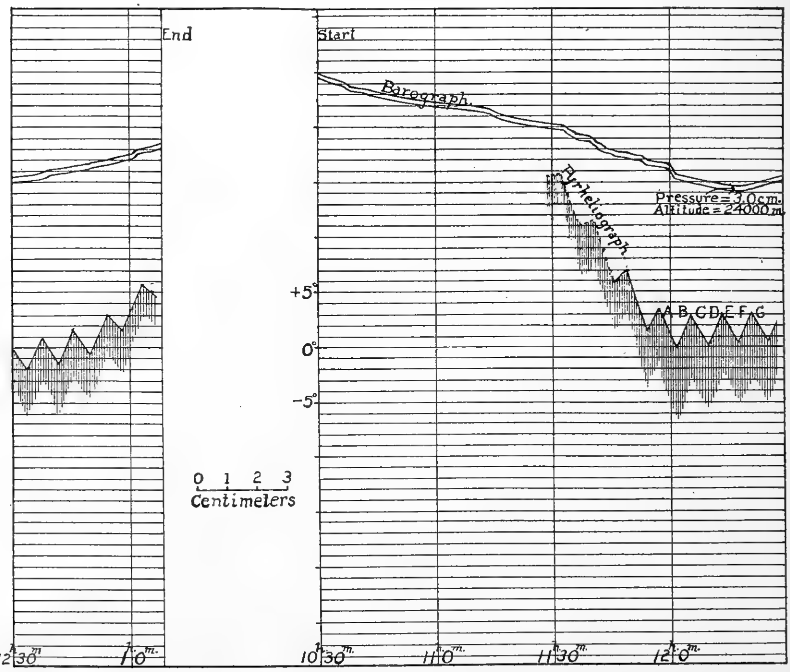


FIG. 9.—Balloon Pyrheliometer Record, July 11, 1914. (From a Tracing.)

clear and good. Unfortunately it was submitted to the process of toning, without being first photographed, and became so faint that it is quite impossible to reproduce it, although it is still readable.

Accordingly we give merely the readings made upon the original, and their reduction. Figure 9 is from a tracing made to represent the march of the record.

The pyrheliometer record consists of a series of zigzag reaches of shading corresponding to the up and down marches of the mercury column. We shall principally confine attention to those marked *A, B, C, D, E, F, G,* which represent the solar radiation measured just before the instrument reached maximum elevation. We do this because: (1) As stated above, the earlier part of the records are of little value owing to the bore of the thermometer being foul for temperatures above $+10°$. (2) A defect in the record occurs just after the balloons began to descend, first owing to a jerkiness, and then owing to crossing the seam in the paper, which renders the next two following readings doubtful. (3) There is doubt as to the elevation at the time of the last descending records, because the barometer arm did not work quite free. (4) The record is finally lost in clouds. All readable records are, however, given for what they may be worth.

CORRECTION TO REDUCE TO VERTICAL SUN

The extreme width of the degree marks on the record during heating *B, D, F,* was measured and found 1.40 millimeters. Inclining the pyrheliometer, first 15.5° N., then 15.5° S., when exposed to the sun, was found to shift the degree marks through a total range of 0.89 mm. Subtracting width of trace, 0.31 mm., and dividing by 2, we find the record sheet is within the pyrheliometer at a distance X, such that X tangent $15.5° = 0.29$ mm. Hence $X = 1.04$ mm. From this it follows that the tangent of the half angle of the cone swept through by the sun rays was $\frac{1.40 - 0.31}{2 \times 1.04}$. Hence the half angle of the cone is 27° 40′. At Omaha, on July 11, at noon the sun's zenith distance was 19° 5′. Hence the pyrheliometer was swinging in a cone whose half angle was $27° 40' - 19° 5' = 8° 35'$.

From these data it follows that the mean value of the cosine of the inclination of the sun's rays upon the pyrheliometer disk at noon was 0.934. But if the instrument had been stationary this value would have been 0.945. Hence the conical rotation produced a change of 0.011. This value has been applied as a correction to the values of cosine Z, corresponding to the several sun exposures. It is probable that the correction is a little too small, because the record

of the degree marks is naturally less wide than it would have been if time had been allowed for full photographic effect at the extremes of the swing.

READINGS ON BEST THREE RECORDS OF JULY 11, 1914

	Cooling A	Heating B	Cooling C	Heating D	Cooling E	Heating F	Cooling G
	2.53	1.34	1.78	1.90	1.96	2.10	1.65
	2.22	1.45	1.77	1.78	1.86	2.00	1.53
	2.39	1.33	1.84	1.77	1.97	1.90	1.40
	2.64	1.50	1.88	1.75	1.92	1.98	1.50
	2.40	1.34	1.90	1.88	1.82	1.82	1.61
	2.55	1.52	1.91	...	1.84	1.78	...
Means	2.45	1.41	1.85	1.82	1.89	1.91	1.54
		2.15		1.87		1.715	
Corrected heating........		3.56		3.69		3.625	

SUMMARY OF READINGS AND REDUCTIONS

Watch time	Corrected hour angle East	Cosine Z	Cosine Z corrected for rotation	Pyrheliometer reading	Reading $X\frac{0.451}{\cos z}$
$11^h 55^m$	$0^h 34^m$	0.936	0.925	3.56	1.736
12 04	0 25	.940	.929	3.69	1.791
12 12	0 17	.942	.931	3.625	1.756
12 20	0 09	.943	.932	3.225	1.561
	West				
12 36	0 07	.945	.934	3.11	1.501
12 44	0 15	.944	.933	3.58	1.730
12 52	0 23	.941	.930	3.09	1.499

The solar radiation indicated by the mean value of the first three records, which are by far the best, is 1.761 calories per sq. cm. per minute. Reduced to mean solar distance and adding 1 per cent for clock rate, it becomes

1.84 calories per sq. cm. per minute.

As will be shown, the mean altitude at this time was about 22,000 meters, and the corresponding pressure about 3 centimeters. In our opinion an increase of about 2 per cent would be a proper allowance for the extinction in the atmosphere above this altitude, considering atmospheric scattering as 1 per cent, and atmospheric absorption 1 per cent.

BAROMETRY AND ALTITUDE

The following results are given by the observations of the U. S. Weather Bureau, as indicated in communications quoted:

UNITED STATES DEPARTMENT OF AGRICULTURE,
WEATHER BUREAU,
OFFICE OF THE CHIEF,
WASHINGTON, D. C., MARCH 15, 1915.

Dr. C. D. Walcott,
Secretary, Smithsonian Institution,
Washington, D. C.

DEAR SIR:

Replying to your letter of March 13, 1915, no readings of pressure and temperature were taken preceding the morning ascension of July 11, 1914. However, a reading was taken after the ascension, at 1 p. m., and another just preceding the second ascension, at 4 p. m. These readings were:

	Pressure	Temperature
At 1 p. m.	732.5 mm.	32.3° C.
At 4 p. m.	732.0 mm.	33.1° C.

The values at the Weather Bureau Station in Omaha at these hours were:

	Pressure	Temperature
At 1 p. m.	730.8 mm.	35.6° C.
At 4 p. m.	730.2 mm.	35.6° C.

Applying these differences, +1.8 mm. for pressure and —2.8° C. for temperature, to the value at 10.30 a. m. at Omaha, viz., 731.5 mm. and 32.2° C., we get 733.3 mm. and 29.4° as the probable values at Fort Omaha just preceding the first ascension, or 10.30 a. m.

Very respectfully,
C. F. MARVIN,
Chief of Bureau.

UNITED STATES DEPARTMENT OF AGRICULTURE,
WEATHER BUREAU,
OFFICE OF THE CHIEF,
WASHINGTON, D. C., MARCH 9, 1915.

Dr. C. D. Walcott,
Secretary, Smithsonian Institution,
Washington, D. C.

DEAR SIR:

I inclose herewith the data for July 11, 1914, requested by you in your letter of January 29, 1915. They include, for the first ascension, when the balloon pyrheliometer was taken up, altitudes each minute as long as the balloons could be observed at both stations; for the second ascension, in the afternoon, temperatures at those levels in which the temperature-altitude relation changed, and interpolated values at 500-meter levels up to 5,000 meters, and at 1,000-meter levels above 5,000 meters. Pressures also are given, wherever it was possible to compute them. A considerable portion of the record has been rubbed off, by reason of its having lain in a mud pond for some days. There were several pounds of mud in the instrument when it was received. All altitudes were computed from the two-station theodolite observations.

The ascensional rates for the two ascensions are almost identical up to 6,000 meters. *Assuming* that they continue in this relation, a curve extended for

the first ascension, as shown in the accompanying chart [not here shown], indicates an altitude of 25,600 meters at the time one of the balloons burst.

Very respectfully,

C. F. MARVIN,

Chief of Bureau.

TEMPERATURES AT DIFFERENT ALTITUDES IN BALLOON ASCENSION, JULY 11, 1914, P. M.

Time p. m.	Altitude *m.*	Pressure *mm.*	Temp. °*C.*	Remarks
4:02	312	732.0	33.1	Balloon launched.
......	500	.....	33.2	
4:04.4	631	706.4	33.3	
4:07.3	962	681.0	29.8	
......	1,000	.....	29.7	
4:11	1,503	640.1	26.0	
......	2,000	.....	21.7	
4:18.2	2,493	.....	17.5	
......	3,000	.....	14.0	
......	3,500	.....	10.8	
4:25.3	3,645	.....	9.9	
......	4,000	.....	9.6	
4:28.8	4,447	.....	9.1	
......	4,500	.....	8.6	
4:32.2	4,976	431.5	4.8	
......	5,000	.....	4.7	
......	6,000	.....	— 1.7	
......	7,000	.....	— 7.9	
4:44.1	7,592	309.9	—11.5	
......	8,000	.....	—13.4	
4:46.8	8,597	280.5	—16.0	
4:49	8,930	265.3	—17.9	
......	9,000	.....	—18.3	
......	10,000	.....	—24.8	
4:55.1	10,442	220.3	—27.6	
......	11,000	.....	—31.8	
5:01.8	11,572	185.5	—35.9	
......	12,000	.....	—38.7	
......	13,000	.....	—45.2	
5:08.7	13,348	145.5	—47.0	
......	14,000	.....	—48.8	
5:13.7	14,641	.....	—52.0	Lowest temperature.
......	15,000	.....	—51.5	
5:15.7	15,026	.....	—51.5	
5:19.2	15,457	.....	—48.3	
......	16,000	.....	—48.3	
5:22.4	16,855	.....	—48.3	
......	17,000	.....	—46.6	
5:24.3	17,106	.....	—45.2	Clock stopped.
5:28	18,164	.....	....	Balloon burst.

ALTITUDES OF BALLOON, DETERMINED FROM THEODOLITE READINGS AT TWO STATIONS, JULY 11, 1914, A. M.

Time a. m.	Altitude	Remarks
10:30.3	312	Balloon launched.
10:32	720	
10:33	1,016	
10:34	1,286	
10:35	1,392	
10:36	1,606	
10:37	1,760	
10:38	1,900	
10:39	2,022	
10:40	2,166	
10:41	2,280	
10:42	2,424	
10:43	2,585	
10:44	2,688	
10:45	2,898	
10:46	2,982	
10:47	3,178	
10:48	3,358	
10:49	3,568	
10:50	3,718	
10:51	3,876	
10:52	3,970	
10:53	4,159	
10:54	4,270	
10:55	4,528	
10:56	4,682	
10:57	4,950	
10:58	5,052	
10:59	5,122	
11:00	5,218	
11:01	5,538	
11:02	5,492	
11:03	5,825	
11:04	6,122	
11:05	6,006	Balloon disappeared from view of observers at Creighton College.
p. m. 12:17.7		Balloon burst.

CALIBRATION OF THE BAROMETRIC RECORD OF JULY 11, 1914

This record is marred by the sticking of the aluminum arm at middle deflections, both in rising and falling flight. Fortunately the arm appears to have been free at maximum elevation, as shown by the perfectly normal inflection of the record at precisely the time when

the two balloons were observed to burst. Accordingly while no suspicion attaches to the record at maximum elevation, it is worthless at intermediate elevations.

The barometer element was calibrated by enclosure of the whole instrument in a brass box from which air could be exhausted, and of which the temperature was regulated by immersion in a stirred bath of gasoline cooled by expansion of liquid carbon dioxide. In one set of experiments the sensitiveness of the element to change of pressure was determined at several constant temperatures ranging from +34° C. to —49° C., and the change of zero with change of temperature was determined as a correction. In another set of experiments, both temperature and pressure were simultaneously lowered to correspond with the temperatures and pressures indicated by the foregoing results of the Weather Bureau observers.

We assume that at the time of launching at Omaha, the instrument, being shone upon by the sun, was 5° in excess of the air temperature, and hence at +34° C. We assume that at the maximum elevation the instrument was at —37° C.

From experiments of December 26, 1914, and February 1 and 4, 1915, we find that the zero of the barometric element changed linearly at the rate of 0.123 mm. per degree, in the sense to diminish the barometric deflection attending falling pressure. Hence for a fall of 71° the correction is 8.7 mm.

From the record of July 11, 1914, the barometric deflection is 37.8 mm. at highest altitude. Corrected deflection, 46.5 mm. From numerous experiments at various constant temperatures, 76.4 cm. mercury pressure corresponds to a deflection on our record of 50.3 mm. Hence for July 11, 1914, the change of pressure was $\frac{46.5}{50.3} \times 76.4 = 70.7$ cm. Hg. The barometer reading at Fort Omaha was 73.33 cm. Hence, by these experiments, the pressure at maximum elevation was 2.63 cm. Hg.

Again, on March 18, 1915, a change of pressure of 72.3 cm. Hg., and accompanying change of temperature from +34.8° to —30°,[1] gave a barometric deflection of 40.0 mm. Hence, from +34° to —37° would have given a deflection of 39.1 mm. Hence, the change of pressure on July 11 was $\frac{37.8}{39.1} \times 72.3 = 70.0$.

Hence, by these experiments the pressure at maximum elevation was 3.33 cm. Hg. As a mean result, we decide that at maximum

[1] Here the carbon dioxide used for cooling purposes was exhausted.

elevation the barometric pressure was 2.98 cm. Hg., or in round numbers, 3.0 cm. Hg. From our examination of the records of various balloon flights at Omaha and Avalon, we suppose this would be regarded as corresponding to an elevation of 24,000 meters, which is in good agreement with the results obtained by theodolite work.

COMPARATIVE RESULTS OF PYRHELIOMETRY AT REDUCED ATMOSPHERIC PRESSURES

In a recent publication, Prof. H. H. Kimball gives the highest value of solar radiation ever observed at Washington, for zenith distance 60°, as 1.51 calories per cm.^{2} per min., observed on December 26, 1914. Reduced to vertical sun and mean solar distance, this result would have been about 1.58 calories.

The highest values observed on Mt. Wilson are those of November 2, 1909, and yield to a similar reduction 1.64 calories, at mean solar distance and vertical sun.

For Mt. Whitney, for the maximum obtained on September 3, 1909, the reduced value is 1.72 calories at mean solar distance and vertical sun.

In balloon flights of August 31, September 28, and October 19, 1913, Dr. A. Peppler of Giessen observed with an Ångström pyrheliometer at great altitudes. On September 28 the results were, in his opinion, vitiated by a defect of the apparatus. On August 31, the highest result, as reduced by Peppler to the Smithsonian scale of pyrheliometry, was 1.77 calories, obtained at zenith distance 45°, altitude 5,900 meters, air pressure 36.5 cm. This result, however, is not a complete Ångström measurement depending on "left, right, left" readings, and therefore may be vitiated by galvanometer drift. Moreover, it stands very high as compared with others of that date, and, indeed, much higher than others of that date obtained at greater altitudes. On October 19, the highest complete result was 1.67 calories, obtained at zenith distance 61°, altitude 7,500 meters, air pressure 29.8 cm. This result is in good agreement with the others of that date. Peppler regards the results of October 19 as his best. When reduced to zenith sun and mean solar distance, the result of October 19 comes out about 1.755 calories per cm.^{2} per minute.

These direct observations from manned balloons are very meritorious, and of course entitled to far greater weight than those obtained at similar altitudes in our free balloon work at Avalon, in 1913. Hence, although our results there were in complete accord with Peppler's, we have not thought it worth while to give them.

Peppler intended to repeat the work in 1914 at greater altitudes, but we fear this may have been one of the valuable things cut off by war.

In figure 10 we give a plot of the pyrheliometer results at various altitudes, as just collected. It seems to us that, with the complete accord now reached between solar constant values obtained by the spectro-bolometric method of Langley, applied nearly 1,000 times in 12 years, at four stations ranging from sea level to 4,420 meters, and

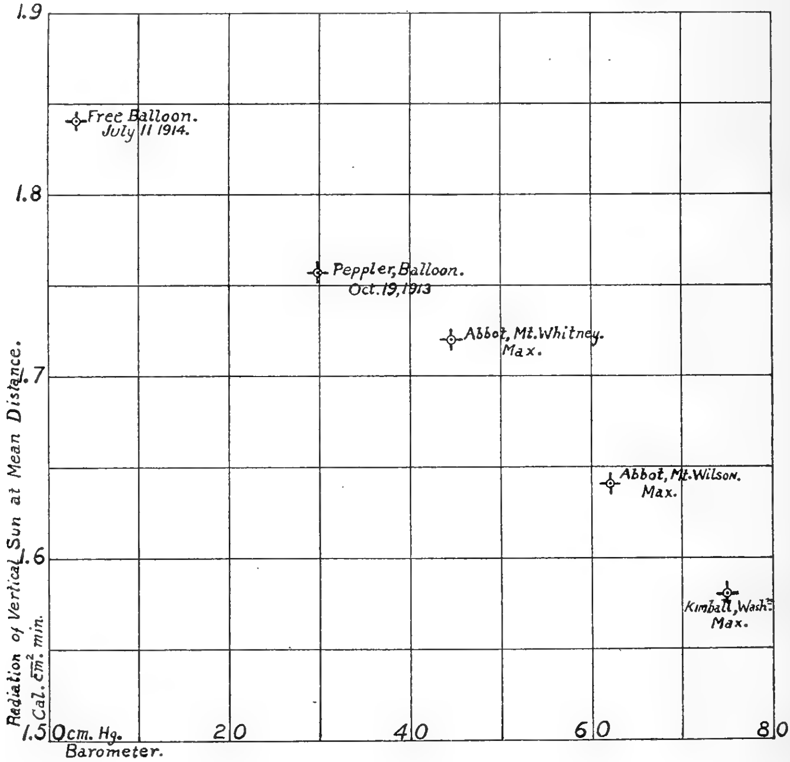


FIG. 10.—Pyrheliometry at Great Altitudes.

from the Pacific Ocean to the Sahara Desert; with air-masses ranging from 1.1 to 20; with atmospheric humidity ranging from 0.6 to 22.6 millimeters of precipitable water; with temperatures ranging from 0° to 30° C.; with sky transparency ranging from the glorious dark blue above Mt. Whitney to the murky whiteness of the volcanic ash filling the sky above Bassour in 1912, it was superfluous to require additional evidence.

But new proofs are now shown in figure 10. This gives the results of an independent method of solar constant investigation. In this

method the observer, starting from sea level, measures the solar radiation at highest sun under the most favorable circumstances, and advances from one level to another, until he stands on the highest practicable mountain peak. Thence he ascends in a balloon to the highest level at which a man may live. Finally he commits his instrument to a free balloon, and launches it to record automatically the solar radiation as high as balloons may rise, and where the atmospheric pressure is reduced to the twenty-fifth part of its sea level value. All these observations have been made. They verify the former conclusion; for they indicate a value outside the atmosphere well within the previously ascertained limits of solar variation.

Our conclusion still is that the solar constant of radiation is 1.93 calories per sq. cm. per minute.

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THE MICROSPECTROSCOPE IN MINERALOGY

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THE MICROSPECTROSCOPE IN MINERALOGY

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The possibilities of the microspectroscope in the identification of minerals and the study of their composition have apparently not been generally appreciated by mineralogists. Occasional articles in the journals devoted to physics and microscopy have contained references to a few minerals; three contributions to the subject from a mineralogical point of view have appeared in recent years—brief discussions of absorption spectra in Miers' "Mineralogy"[1] and in Smith's "Gem-Stones"[2] and F. J. Keeley's "Microspectroscopic Observations"[3]; but in none of these is it treated as fully as might be desired. The present paper comprises descriptions of the spectra of a much larger number of minerals than has heretofore been examined.[4]

The apparatus which has proved most satisfactory in the studies here described consists of a Crouch binocular microscope stand, fitted with a 37 millimeter objective, an Abbe-Zeiss "Spectral-Ocular"[5] in the right hand tube, and in the other an ordinary low-power eyepiece, marked on the lower lens at the point where the image of a mineral grain falls when it is visible through the spectroscope slit; the prism which diverts part of the light into the left

[1] Macmillan and Co., New York and London, 1902; pp. 275-276.

[2] Methuen and Co., London, 1912; pp. 59-62.

[3] Proc. Acad. Nat. Sci. Phila., 1911, pp. 106-116; Mr. Keeley has made a number of valuable suggestions in connection with the preparation of the present paper, which are herewith gratefully acknowledged.

[4] Col. Washington A. Roebling, of Trenton, N. J., kindly furnished the writer with samples of a number of rare minerals from his very complete collection to supplement those available at the Museum.

[5] Mr. Keeley states that he finds a Browning or Beck microspectroscope ocular useful for preliminary examinations; a Wallace grating-microspectroscope, obtained through the kindness of Mr. Thomas I. Miller, of Brooklyn, N. Y., was also tried, but the spectra it yields are too faint for mineral work in general.

hand tube is withdrawn after the mineral grain has been centered, so as to permit as much light as possible to pass through the spectroscope. A binocular microscope is not absolutely necessary, but frequent readjustments of the scale and slit have to be made if the mineral is observed by swinging out the upper part of the spectroscope and the slit holder.

Light may be obtained from any source yielding a brilliant white light, such as a Welsbach burner or a Nernst lamp, although sunlight or daylight are objectionable because of showing the Fraunhofer lines. For the study of minerals in thin sections, and in a few special cases mentioned below, this is reflected up through the specimen by means of the sub-stage mirror. In the majority of cases, however, better results are obtained by concentrating the light laterally on the specimen by a lens or by a parabolic mirror attached to the objective, and observing the brightest portion of its path. Not only does the latter plan yield the better spectra (apparently because they are connected with fluorescence phenomena), but it permits the examination of crystals on the matrix, gems in their settings, and other similar objects, and, further, does not require any polishing or special preparation of surfaces. The more intense the light the smaller the grains which can be studied in this way.

To set the wave-length scale of the instrument accurately a sodium flame is used, scale division 058.9[1] being brought into coincidence with the yellow (D) line. In addition, a small slip of "didymium" glass,[2] which can be readily inserted at the opening where light for the comparison spectrum enters, is very convenient, the interval between the strong absorption bands of neodymium and praseodymium in the yellow being set at about 058 (580 $\mu\mu$). See figure 1.

The scale of the instrument is graduated in hundredths of microns, but, except at the extreme red end, tenths of divisions can be readily estimated, and it is most convenient to state measurements in three-figure wave lengths. Since the edges of many of the absorption bands are so hazy that they cannot be located exactly, and since the positions of bands vary somewhat in different directions in anisotropic substances, as well as from one crystal to another in minerals of variable composition, readings are liable to an uncertainty of about 5 units. However, as the object of the present paper is not to establish wave lengths, but to record the general characteristics

[1] This corresponds to wave length 589 $\mu\mu$; all measurements are stated in the latter form.

[2] Obtainable from the Corning Glass Co., Corning, N. Y.

of the absorption spectra of the different minerals for determinative purposes, this degree of accuracy is quite sufficient.

The light diffused by mineral grains shows in most cases more intense absorption bands than that transmitted directly through them, yet it must penetrate considerably to be affected at all, so that only transparent or fairly translucent minerals yield any effects; in addition they must be more or less distinctly colored. The number of minerals suitable for microspectroscopic study is therefore rather limited, but the fact that the specimens need not be scratched, broken,

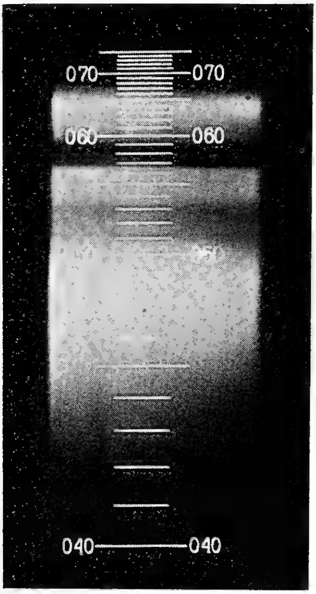

FIG. 1.—The wave length scale of the Abbe-Zeiss microspectroscope, with the absorption spectrum of "didymium" glass, the interval between the two strongest bands of which is set at 058. The several bands lie at 067.5, 062.5, 059.0, 058.2, 057.4, 053.1, 052.5, 051.2, 048.0, 044.8, and 043.3. Transmitted light; source, Welsbach burner; exposure 1 hour; Wratten and Wainwright Panchromatic plate.

or altered in any way renders the method of considerable use in the identification of crystals too valuable to be broken up for the usual tests, and in particular of cut gems, whether free or in their settings. Even where other methods are applicable the spectra may serve as confirmatory tests.

This method has proved especially useful in determining the genuineness of rubies, sapphires, and emeralds sent to the Museum for examination and report, in picking out corundum, zircon, and

garnet from gem gravels in the collection, in distinguishing greenockite from other minerals occurring as yellow coatings, and in the identification of a number of other minerals. The microspectroscope may also be applied to the measurement of the thickness of iridescent films and the discovery of the origin of various color phenomena, but this phase of the subject has been fully discussed by Keeley in the paper cited and need not be further considered here.

THE RARE EARTH MINERALS

The strong absorption bands shown by salts of certain of the rare earth metals have long been recognized as a good means for their detection in solutions, and several writers have pointed out that minerals containing them also show the bands, and have called attention to the value of this property for identification of these minerals. In the preparation of this paper all available minerals known to contain appreciable amounts of the rare earths have been examined. Most of the light colored ones, as listed in the tables below, were found to exhibit two or more of these bands, all except the violet calcite yielding much more intense effects when viewed at an angle to the path of the light than when observed in the direction of the transmitted ray. Not only is the presence of these absorption bands useful as a means of distinguishing rare earth minerals from all others, but it may even serve to differentiate certain of the individual species; the positions and intensities of the bands vary from one to another in a fairly characteristic way, although identification on this basis alone is not always certain, since slight variations may occur between different grains of the same mineral.

The presence of the rare earth metals in calcite from Joplin, Missouri, was discovered by W. P. Headden[1] by analytical procedure, and has recently been reaffirmed by Pisani,[2] the amounts present being mostly less than 0.05 per cent. Headden found that the violet calcite from this locality gives "didymium" absorption bands. With the microspectroscope this material shows, by transmitted light, two distinct bands, matching approximately those of neodymium in the "didymium" glass comparison spectrum, and being probably due to that element, the salts of which have a violet tint. The most deeply colored specimens show these bands when as thin as 3 millimeters, although the paler tinted varieties show them only in greater thicknesses, while the colorless and yellow portions

[1] Amer. Journ. Sci., ser. 4, vol. 21, 1906, p. 301.

[2] Compt. rend., vol. 158, 1914, p. 1121.

of the same crystals fail to show the slightest trace of them. Violet calcite from another locality, Rossie, New York, also shows these bands faintly.

On heating the violet calcite in an air bath to about 400° for ten minutes the color is completely discharged (yellow light being emitted) and the absorption bands disappear. The simplest explanation of this behavior is that the rare earths are originally present as carbonates (in solid solution of the mix-crystal type), and in that form show the absorption bands, but that, on heating, these compounds are converted into oxides, which do not show them. Headden's observation that the yellow calcite from Joplin contains more rare earths than other varieties can be readily reconciled with the absence of bands in its spectrum by recognizing that the metals may be present in it only as oxides in the first place.

It is therefore concluded that violet calcite probably owes its color to the presence, in mix-crystal form, of traces of a carbonate of neodymium.

Yellow titanite labeled as from " Mont Blanc " and brown apatite from several places in Ontario, Canada, show the neodymium bands with about the same intensity as the violet calcite, although the violet color is hidden by stronger ones due to iron or other constituents. The remainder of the minerals listed in the rare earth tables are well known compounds of those elements.

URANIUM MINERALS

Transparent minerals containing uranium in the uranic form show an absorption spectrum consisting of several bands in the green, blue, and violet, viewing the grains at an angle to the path of the light giving the most brilliant effects. The variation in the positions and relative intensities of these bands from one species to another is particularly well marked and of some diagnostic value, although more than 30 per cent of uranium must be present, and many minerals with even this amount yield no spectra.

Some specimens of the mineral zircon yield, as has long been known, a number of absorption bands, which correspond to those shown by uranium salts after reduction with zinc, that is, when in the uranous condition. This uranium, which is present in minute amount, mostly less than 0.5 per cent, has the same valence as the zirconium and no doubt replaces a part of it, giving a blue color to the mineral, which may, however, be hidden by other tints, due to iron, manganese, etc. It therefore cannot be predicted whether a given crystal of zircon will show a spectrum or not, but, on the other

hand, if an unknown mineral shows these bands, it is reasonably certain to be zircon, for no other mineral is as yet known to contain uranous uranium.

THE GARNET GROUP

The red colors of garnets of the varieties pyrope, almandite, spessartite, and essonite have been variously interpreted as due to gold,[1] tin,[1] iron,[2] chromium,[3] manganese,[4] and vanadium.[5] Two different sets of bands seem to be superposed in the spectra of the members of this group, (A) a narrow band at 620 and a broad one centering at about 590 (these often coalesce); and (B) two broad bands at about 530 and 500. In order to correlate, if possible, these spectra with the amounts of the last three of the above listed elements, specimens were analyzed by fusing with sodium carbonate and nitrate, extracting with water, comparing the color of the solution with that of potassium chromate of known strength, then acidifying with sulfuric acid, evaporating, adding hydrogen peroxide, and titrating the vanadium with standard permanganate[6]; manganese being determined colorimetrically in the residues (except in the case of spessartite, where the average of published analyses was used). The results were as follows:

Variety	Locality	Color	Spectra		Cr Per ct.	V Per ct.	Mn Per ct.
			A	B			
Pyrope.....	Bohemia........	deep red..	strong.	none...	1.12	none	1.40
Almandite..	Wrangell, Alaska	deep red..	distinct	strong.	0.03	0.02	1.45
Almandite..	India...........	violet-red.	distinct	strong.	0.02	0.03	1.20
Spessartite..	Amelia C. H., Va.	brown....	distinct	distinct.	0.02	0.01	33.65
Essonite....	Ceylon..........	brown-red	distinct	none...	0.02	none	0.25
Essonite....	Ceylon..........	brown....	faint..	distinct.	0.01	0.01	0.35

In this table it is evident that spectrum A is connected with the presence of chromium, while B is, if anything, related to the vana-

[1] "In former ages . . . . it was believed that gold and tin were the coloring principle of garnet." Feuchtwanger, Treatise on Gems, New York, 1838, p. 18. I am indebted to Dr. William S. Disbrow, of Newark, N. J., for calling my attention to this reference.

[2] According to most writers; but inspection of analyses shows no relation between the color and the content of either ferrous or ferric iron.

[3] First detected by Klaproth, Beitr. Chem. Min., vol. 5, 1810, p. 171; mentioned as the cause of color of pyrope in many books on precious stones.

[4] Regarded as the cause of the color by various writers, and of the absorption spectrum by Brun, Arch. sci. phys. nat., ser. 3, vol. 28, 1892, p. 410, and by Keeley, loc. cit.

[5] Uhlig, Verh. nat. Ver. preuss. Rheinl. Westfal., vol. 67, 1910, p. 307; Zeits. Kryst. Min., vol. 53, 1913, p. 203.

[6] Cain and Hostetter, Journ. Amer. Chem. Soc., vol. 34, 1912, p. 274.

dium content. Many artificial salts of the former metal, as well as the chlorite minerals colored violet by it, show spectrum A, so it may be considered proved that one factor in the color of magnesium (and manganese) garnets is the element chromium. (Calcium garnets, which are colored green by this element, show an entirely different spectrum.) Spectrum B, it must be admitted, has never been observed in minerals or artificial compounds of vanadium, but no other silicates containing vanadium as a red compound have been available for study (the green roscoelite showing no bands) and as the mode of combination has great influence on the character of the spectra shown by a given element, it may be regarded as probable that vanadium is a second factor in the color of garnets. The total manganese shows no connection with the spectrum, and the presence of more or less ferrous iron in all garnets precludes the possibility of the existence of any manganic compound.

TABLES

The results of the examination of about 200 minerals with the microspectroscope are here presented in tabular form. Only a third of them exhibit distinctive spectra, but as the absence of bands may also have diagnostic value in some cases, it has seemed best to list all those tried. The wave lengths of bands which are especially characteristic of the various minerals are given in bold face type, and of those which are faint and difficult to see in parentheses. The limits of visibility (recorded as "To 700, 440 on," etc.) vary rather widely with the thickness of mineral through which the light passes, but are added for the sake of completeness.

To increase the practical usefulness of the tables a determinative table, or analytical key, is added after the lists of mineral spectra. It is based on general character of spectrum, number of bands and mineral colors, and covers all minerals showing bands of sufficient intensity for diagnostic purposes.

Finally, as this method may also prove useful for demonstrating the presence or absence of certain chemical elements, a table of the elements showing spectra, with their forms, and the limits to the amounts present, is also given. It should be noted here that the elements causing the colors and absorption bands of some minerals are as yet unknown; thus, the band at or near wave length 605 in the rare earth minerals with the yttrium group in excess cannot be ascribed to any known element; and in the other tables interrogation points (?) in the "coloring elements" columns show the lack of information in many cases.

MINERALS SHOWING THE RARE EARTH ABSORPTION SPECTRA

Cerium Group in Excess

	Red		Orange		Yellow		Green				Blue		Violet	
Elements causing bands		Nd	Er	Nd	Pr	Nd	Sm	Nd	Nd, Er	Nd	Pr, Sm	Pr	Pr	
Tysonite	To 700	**675**	(650)	(623)	**595**	580–570	...	(532)	522	(513)	(485)	...	...	440 on
Bastnäsite	To 690	675	(650)	(623)	(590)	**579 569**	...	(532)	522	(511)	(485)	...	...	450 on
Parisite	To 690	675	...	**623**	**590**	to **570**	...	533	**522**	**512**	485	(470)	(445)	440 on
Cordylite	To 680	(675)	...	...	(590)	**581** (575)	...	(533)	521	512	(485)	470	...	440 on
Lanthanite	To 680	(675)	...	(620)	(590)	**579 570**	...	(532)	**520**	**510**	(485)	(470)	(445)	440 on
Calcite, violet	To 690	...	...	...	...	**582**	...	...	(525)	...	...	...	...	430 on
Cerite	To 680	(675)	...	(620)	**590**	to **570**	...	(533)	(525)	(512)	(485)	...	...	440 on
Titanite, yellow	To 670	...	...	...	...	(585)	...	...	(525)	...	...	...	...	460 on
Mosandrite	To 680	...	...	...	...	(585)	...	...	(525)	...	...	...	...	440 on
Tritomite	To 670	...	...	...	...	(585)	...	...	(525)	...	...	...	...	460 on
Freyalite	To 680	(675)	...	...	(590)	**585 575**	...	**530**	(525)	(512)	(485)	...	...	460 on
Britholite	To 680	(675)	...	...	(590)	**588–578**	...	530	(520)	(512)	(485)	...	..	460 on
Aeschynite	To 670	...	...	...	...	(585)	...	...	(525)	...	...	...	...	440 on
Pyrochlore	To 680	...	...	...	...	**588–578**	...	...	(525)	...	...	...	...	460 on
Microlite	To 670	...	...	...	...	(585)	...	...	(525)	...	...	...	...	450 on
Monazite	To 690	**675**	(645)	622	**590**	to **570**	(555)	(532)	**523**	512	485	...	...	450 on
Rhabdophanite	To 690	**675**	645	622	**595**	to **570**	(555)	533	**524**	512	485	(470)	(445)	430 on
Churchite	To 690	(675)	...	(620)	**590**	**578**	...	(535)	524	(510)	(485)	...	...	440 on
Apatite, brown	To 670	...	...	...	...	(585)	...	...	(525)	...	...	...	...	460 on
Gummite	To 660	...	...	...	...	585	...	...	**525**	...	...	...	...	460 on
Yttrium Group in Excess					*									
Rowlandite	To 660	...	(645)	...	(600)	**585–575**	(555)	...	**522**	...	(485)	...	...	450 on
Yttrialite	To 670	...	(645)	...	(600)	(585)	(555)	...	(522)	...	(485)	...	...	460 on
Fergusonite	To 670	...	...	...	...	(585)	(555)	...	(522)	...	...	...	...	450 on
Yttrotantalite	To 670	...	(650)	...	(600)	(585)	(555)	...	**522**	...	...	...	...	460 on
Xenotime	To 660	...	**645**	...	**605**	...	**555**	...	522	...	(485)	...	...	450 on

Tritomite includes caryocerite, melanocerite, and steenstrupine; fergusonite includes sipylite; yttrotantalite includes risörite; the following show no spectra, being for the most part too opaque: allanite, ankylite, blomstrandite, cenosite, euxenite, gadolinite, hatchettolite, loranskite, polycrase, rogersite, samarskite, tengerite, and thorite. Certain specimens of autunite and other secondary uranium minerals, when derived from rare earth bearing primary minerals, show the same spectrum as gummite.

* See last paragraph on page 7.

MINERALS SHOWING THE URANIUM ABSORPTION SPECTRA

Uranic Uranium

	Red	Orange	Yellow	Green		Blue			Violet			
Liebigite	To 680	...	...	(535)	(515)	495	(480)	**463**	455	(440)	430	on
Voglite	To 670	...	...	...	...	504	**488**	472	458	**447**	440	on
Autunite	To 680	...	(550)	(532)	(**515**)	**499**	484	(468)	(455)	**445**	440	on
Uranocircite	To 680	...	(**552**)	(**535**)	515	495	(485)	(470)	(455)	448	440	on
Torbernite	To 670	...	...	...	...	**503**	**487**	470	458	**445**	430	on
Uranospinite	To 680	...	...	(530)	...	**495**	482	(467)	(455)	(440)	430	on
Zeunerite	To 670	...	...	...	...	505	**489**	472	459	**448**	430	on
Johannite	To 680	...	...	...	...	**497**	**479**	(466)	(450)	...	440	on
Uranium glass	To 630	595	570	545	525	**505**	**485**	465	...	...	460	on

Liebigite includes uranothallite; johannite includes uranochalcite and voglianite; the following do not show definite spectra: carnotite, rutherfordine, trögerite, uraconite, uraninite, uranophane, uranopilite, uranosphærite, walpurgite, and zippeite; it may further be noted that specimens labeled phosphuranylite have proved in almost every case to show the spectrum of autunite, and have yielded calcium on qualitative examination, but an authentic specimen of this mineral in the Brush collection, loaned for examination through the kindness of Prof. Ford, showed no spectrum beyond slight general absorption in the blue. See also note to rare earth table.

Uranous Uranium

	Red			Orange		Yellow		Green		Blue		Violet
Zircon, blue	To 690	685	(660)	**651**	618	**588**	560	537	**512**	483	(460)	440 on
Zircon, green	To 690	685	(660)	**651**	618	**588**	(560)	537	**512**	483	(460)	440 on
Zircon, yellow	To 690	(685)	...	**651**	(618)	588	...	(537)	(512)	(483)	...	450 on
Zircon, pink	To 690	(685)	...	**651**	(618)	588	...	(537)	512	(483)	...	440 on

Brown, white and colorless zircons do not show spectra.

Color Red, Pink or Orange

	Coloring elements	Red	Orange	Yellow	Green	Blue	Violet
Hematite	Fe'''	To 690	...	...	...	...	440 on
Botryogen	Fe'''	To 680	...	...	560	on	...
Spherocobaltite	Co''	To 680	...	(570 to 540)		...	430 on
Erythrite	Co''	To 680	...	...	**560–540**	(500–490)	430 on
Roselite	Co''	To 680	...	(570 to 540)		...	430 on
Zincite	Mn''	To 680	...	(600–570)	...	510	on ...
Rhodochrosite	Mn''	To 670	...	580 to 540		...	460 on
Rhodonite	Mn''	To 670	...	580 to 540		...	460 on
Zoisite var. thulite	Mn''	To 670	...	...	560–530	...	450 on
Piedmontite	Mn''	To 660	...	...	...	...	450 on
Tourmaline var. rubellite.	Mn''	To 670	...	...	(560 to 490)		430 on
Hübnerite	Mn''	To 680	...	...	...	...	460 on
Corundum, pink	Cr'''	To 700 **680**	...	600–570	...	...	460 on
Corundum var. ruby	Cr'''	To 700 **680**	...	600–570	...	...	450 on
Corundum var. ruby, synthetic.	Cr'''	To 700 **680**	...	600 to 510		...	460 on
Garnet var. pyrope (see text).	Cr'''	To 670	620 to 560		...	...	460 on
Garnet, grossularite, pink.	Cr'''	To 660	(610 to 580)		...	...	460 on
Crocoite	Cr^{vi}	To 670	...	570	on ...	...	...
Cuprite	Cu'	To 700	**630**	...	...	...	450 on
Imitation ruby (Cu-glass).	Cu'	To 680	...	600–560	...	...	460 on
Garnet var. almandite (see text).	$V'''+Cr'''$	To 680	620	**585–570**	530–520	**510–495**	450 on
Garnet var. spessartite.	$V'''+Cr'''$	To 680	(620)	580–565	(540–520)	470	on ...
Rutile	V^{v}	To 680	...	...	...	...	450 on
Vanadinite	V^{v}	To 670	...	580 to 550		490	on ...
Pascoite	V^{v}	To 670	...	...	550	on ...	...
Wulfenite	V^{v}	To 670	...	...	560	on ...	...
Cinnabar	Hg''	To 690	610 to 590		...	...	460 on
Realgar	As''	To 680	...	580 to 540		470	on ...
Proustite	As'''	To 670	...	600–570	...	...	460 on
Pyrargyrite	Sb'''	To 670	610 to 580		...	...	460 on
Halite	?	To 680	...	(580 to 540)		480	on ...
Fluorite	?	To 670	...	...	...	...	440 on
Quartz var. rose-quartz.	?	To 680	...	...	...	...	440 on
Spinel	?	To 680	...	(580 to 540)		...	460 on
Calcite	?	To 670	...	...	...	490	on ...
Beryl	?	To 670	...	...	...	...	440 on
Topaz	?	To 680	...	(570 to 530)		...	450 on

The diagnostic importance of the spectra of the red corundums (shown in reflected light only) was pointed out by Keeley (*op. cit.*, p. 109).

COLOR YELLOW OR BROWN

	Coloring elements	Red	Orange	Yellow	Green	Blue	Violet	
Sphalerite	Fe″	To 680	...	...	...	510	on	...
Goethite	Fe‴	To 650	...	...	550	on		...
Siderite	Fe‴	To 680	...	...	...	470	on	...
Garnet var. andradite	Fe‴	To 670	...	...	...	480	on	...
Garnet var. grossularite	Fe‴	To 670	...	...	...	470	on	...
Vesuvianite	Fe‴	To 660	...	...	...	480	on	...
Staurolite	Fe‴	To 670	...	...	(560–550)	470	on	...
Tourmaline	Fe″	To 650	...	...	...	490	on	...
Copiapite	Fe‴	To 680	...	...	...	490	on	...
Imitation topaz (Fe-glass)	Fe‴	To 660	...	...	...	490	on	...
Corundum	Fe‴	To 670	...	...	...	...	**455**	440 on
Greenockite	Cd″	To 670	...	...	**525–515**	500	on	...
Iodyrite	Ag′	To 680	...	...	...	...	(445)	440 on
Orpiment	As‴	To 680	...	...	...	480	on	...
Wulfenite	Mo^{vi}	To 670	...	...	...	...		460 on
Sulfur	S^o	To 680	...	...	...	480	on	...
Selensulfur	Se^o	To 680	...	...	...	480	on	...
Fluorite	?	To 680	...	...	...	...		440 on
Quartz var. citrine	?	To 670	...	...	...	470	on	...
Cassiterite	?	To 670	...	...	...	...		450 on
Chrysoberyl	?	To 670	...	...	...	...		460 on
Calcite	?	To 660	...	...	...	480	on	...
Smithsonite	?	To 670	...	...	...	...		460 on
Beryl	?	To 670	...	...	...	...		450 on
Olivine	?	To 670	...	...	...	...		460 on
Willemite	?	To 670	...	...	...	...		440 on
Thorite	?	To 670	...	...	...	480	on	...
Topaz	?	To 670	...	...	...	...		460 on
Axinite	?	To 670	...	...	...	...		450 on
Titanite	?	To 660	...	...	...	470	on	...
Apatite	?	To 660	...	...	...	470	on	...
Barite	?	To 670	...	...	...	470	on	...

In addition, many rare earth and uranium minerals, listed in the preceding tables, are yellow or brown in color.

COLOR GREEN

	Coloring elements	Red	Orange	Yellow	Green	Blue	Violet
Corundum........	Fe‴+Ti‴	To 670	...	...	...	...	**455** 440 on
Diopside..........	Fe″	To 670	...	...	...	...	450 on
Actinolite..........	Fe″	To 650	...	...	...	...	460 on
Olivine...........	Fe″	To 670	...	...	...	**500–490**	(460) 430 on
Epidote..........	Fe″+Fe‴	To 670	...	...	...	(478)	**458** 430 on
Tourmaline.......	Fe″	... To	630	...	...	...	450 on
Clinochlore.......	Fe″	To 650	...	...	...	...	460 on
Serpentine........	Fe″	To 650	...	...	...	...	460 on
Melanterite.......	Fe″	To 650	...	...	...	...	450 on
Manganosite......	Mn″	To 700	650 to	575	520	on	
Zaratite..........	Ni″	... To	640	...	...	500	on ...
Cabrerite.........	Ni″	... To	620	...	...	500	on ...
Spodumene var. hiddenite.	Cr‴	...	... To	580	...	500	on ...
Beryl var. emerald.	Cr‴	To 680	**(640)** **(620)**	...	...	470	on ...
Garnet var. demantoid.	Cr‴	To 680	(640) (620)	...	...	510	on ...
Garnet var. uvarovite.	Cr‴	...	... To	570	...	500	on ...
Vesuvianite.......	Cr‴	To 670	...	...	...	480	on ...
Muscovite var. fuchsite.	Cr‴	To 670	(650)	...	...	500	on ...
Atacamite........	Cu″	... To	630	...	...	500	on ...
Malachite.........	Cu″	... To	630	...	...	500	on ...
Aurichalcite......	Cu″	... To	640	...	...	500	on ...
Dioptase..........	Cu″	... To	640 (610 to	580)	...	490	on ...
Chrysocolla.......	Cu″	... To	640	...	...	500	on ...
Tyrolite..........	Cu″	... To	620	...	...	500	on ...
Brochantite.......	Cu″	... To	630	...	...	500	on ...
Natrochalcite.....	Cu″	... To	620	...	...	500	on ...
Imitation emerald (Cu-glass).	Cu″	... To	620	...	...	490	on ...
Roscoelite........	V‴	... To	640	...	...	470	on ...
Calciovolborthite..	V‴	To 650	...	...	...	510	on ...
Fluorite..........	?	To 660	630–610	...	...	500	on ...
Quartz var. chrysoprase.	?	... To	630	...	...	...	450 on
Spinel............	?	To 660	...	...	...	(490)	460 on
Chrysoberyl var. alexandrite.	?	To 690	...	**600–570**	...	(490–470)	560 on
Microcline........	?	To 660	...	...	...	500	on ...
Beryl............	?	To 670	...	...	...	...	450 on
Willemite.........	?	To 660	...	...	...	...	460 on
Datolite..........	?	To 660	...	...	...	...	450 on
Andalusite (gem variety).	?	... To	640	...	**555** 525	510	on ...
Prehnite..........	?	To 670	...	...	...	...	450 on
Titanite..........	?	To 670	...	...	...	500	on ...
Apatite...........	?	To 660	...	...	...	...	450 on
Pyromorphite.....	?	To 660	...	...	...	510	on ...
Variscite.........	?	To 660	...	...	...	500	on ...
Wavellite.........	?	To 660	...	...	...	...	450 on

A few green minerals are included in the rare earth and uranium tables. The absorption band shown by manganosite has recently been observed by Ford (Amer. Journ. Sci., vol. 38, 1914, p. 502).

COLOR BLUE

	Coloring elements	Red	Orange	Yellow	Green	Blue	Violet
Glaucophane	Fe''+Fe'''	To 670	...	...	...	...	440 on
Tourmaline var. indicolite.	Fe''+Fe'''	To 650	...	...	...	...	450 on
Vivianite	Fe''+Fe'''	To 660	...	...	...	...	460 on
Imitation sapphire (Co-glass).	Co''	To 700 **670 to 640**		**600–580**	550–530	...	430 on
Spinel	Co''	... To	640	(590)	**555–545**	(510) **465 to 455**	430 on
Covellite	Cu''	To 650	...	...	...	...	440 on
Boleite	Cu''	To 650	...	...	...	...	450 on
Smithsonite (stained)	Cu''	... To	640	...	...	...	450 on
Azurite	Cu''	To 650	...	...	...	**510–480**	430 on
Calamine (stained)	Cu''	To 660	...	...	...	...	440 on
Turquois	Cu''	To 650	...	...	...	...	440 on
Chalcanthite	Cu''	... To	620	(590 to 550)		...	440 on
Linarite	Cu''	To 650	...	(600–560)	...	...	440 on
Corundum var. sapphire.	Ti'''	To 660	...	...	...	...	425 on
Corundum var. sapphire, synthetic.	Ti'''	To 650	...	...	...	...	430 on
Octahedrite	Ti'''	To 650	...	...	...	...	440 on
Cyanite	Ti''' (?)	To 660	...	...	...	...	430 on
Dumortierite	Ti'''	To 650	...	...	...	...	450 on
Benitoite	Ti'''	To 650	...	...	...	...	425 on
Halite	Na°	To 680	610 to 580		...	...	440 on
Calcite	?	To 660	...	...	...	...	440 on
Beryl var. aquamarine.	?	To 660	...	...	...	...	460 on
Iolite	?	To 680	...	...	...	**500–490**	425 on
Sodalite	?	To 660	...	...	...	...	430 on
Lazurite	?	To 660	...	...	...	...	440 on
Topaz	?	To 660	...	...	...	...	440 on
Euclase	?	To 660	...	...	...	...	450 on
Lazulite	?	To 660	...	...	...	...	460 on
Barite	?	To 660	...	...	...	...	440 on
Celestite	?	To 660	...	...	...	...	440 on

Color Violet or Purple

	Coloring elements	Red	Orange	Yellow	Green	Blue	Violet
Pyroxene var. violan.	Mn'''	To 680	...	...	...	...	440 on
Spodumene var. kunzite.	Mn'''	To 650	...	...	**560–520**	...	440 on
Tremolite var. hexagonite.	Mn'''	To 670	...	(580–570)	...	...	450 on
Hodgkinsonite	Mn'	To 660	...	(590–570)	...	...	450 on
Axinite	Mn''	To 670	...	...	...	...	460 on
Lepidolite	Mn''	To 670	...	(580–570)	...	...	460 on
Imitation amethyst (Mn-glass).	Mn'''	To 650	...	(590)	(545)	...	430 on
Spinel	Co''	To 670	...	(590)	**555–545**	...	(460) 440 on
Chlorite var. kotschubeite, kämmererite, etc.	Cr'''	To 670	(610 to 560)		...	...	450 on
Dumortierite	Ti'''	To 670	...	...	...	...	430 on
Corundum	$Cr'''+Ti'''$	To 700 (680)	...	(590–560)	...	...	450 on
Garnet var. almandite.	V'''	To 670	(620)	**590–570**	540–520	510–490	460 on
Fluorite	?	To 670	...	(600 to 550)		...	440 on
Quartz var. amethyst.	?	To 660	...	...	(520 to 490)		430 on
Diaspore	?	To 660	...	...	...	...	450 on
Apatite	?	To 660	...	...	...	...	440 on

Violet calcite and lanthanite are included in rare earth list.

ANALYTICAL KEY

Group I.—Spectrum Composed of Narrow Bands

Number of bands	Wave length of strongest	Elements	Minerals
10	650	Uranium (uranous)......	Zircon (certain varieties)
9	575	Neodymium + praseodymium	See tables
8	500	Uranium (uranic)......	See tables
6	555	Samarium+erbium....	See tables
2	585	Neodymium (0.005–0.5%)	See tables

Group II.—Spectrum Composed of Broad Bands

A.—Color Red

4	575	Chromium+vanadium.	Garnet (almandite and spessartite)
2	680	Chromium	Corundum (ruby and pink)
2	550	Cobalt................	Erythrite
1	630	Copper (cuprous).......	Cuprite
1	600	Chromium.............	Garnet (pyrope)

B.—Color Yellow

1	520	Cadmium (as sulfide)	Greenockite
1	455	Iron (ferric)..........	Corundum (oriental topaz)

C.—Color Green

2	640	Chromium............	Beryl (emerald)
2	585	?	Chrysoberyl (alexandrite)
2	555	?	Andalusite (gem variety)
2	495	Iron (ferrous).........	Olivine (chrysolite, peridote)
2	460	Iron (ferric)	Epidote
1	455	Iron (ferric)...........	Corundum (oriental emerald)

D.—Color Blue

4	550	Cobalt	Spinel
[3	655	Cobalt.................	Cobalt glass (imitation sapphire)]
1	500	Copper................	Azurite
1	495	?	Iolite

E.—Color Violet

4	575	Chromium + vanadium .	Garnet (almandite)
3	555	Cobalt	Spinel
2	680	Chromium	Corundum (oriental amethyst)
1	540	Manganese (?)	Spodumene (kunzite)

THE ELEMENTS AND THEIR SPECTRA

Elements	Forms	Percentages	Compounds	Average positions of bands
Antimony	Sb'''	18–22	Ag_3SbS_3	610–580
Arsenic	As''	70	AsS	580–540
	As'''	13–15	Ag_3AsS_3	600–570
Cadmium	Cd''	78	CdS	525–515
Chromium	Cr''' (red)	0.1–2.5	$(Al, Cr)_2O_3$	680 600–570
	Cr''' (red)	0.01–3.0	$(Mg, Fe)_3(Al, Cr)_2(SiO_4)_3$	620 585–570
	Cr''' (violet)	3–10	$Mg(Al, Cr)(OH)SiO_4$	(610–560)
	Cr''' (green)	0.1–0.2	$Be_3(Al, Cr)_2(SiO_3)_6$	(640) (620)
Cobalt	Co''	28	$Co_3(AsO_4)_2 \cdot 8H_2O$	560–540 (500–490)
	Co''	0.1–0.5	$(Mg, Co)Al_2O_4$	(590) 555–545 (510) 465–455
Copper	Cu'	89	Cu_2O	630
	Cu''	55	$Cu_3(OH)_2(CO_3)_2$	510–480
	Cu''	26	$CuSO_4 \cdot 5H_2O$	(590–550)
Erbium	Er'''	1–20	$(Y, Er)PO_4$, etc.	645 520
Iron	Fe''	4–25	$(Mg, Fe)_2SiO_4$	500–490 (460)
	Fe'''	0.1–1.0	$(Al, Fe)_2O_3$	455
	Fe'''	4–15	$Ca_2(Al, Fe)_3(OH)(SiO_4)_3$	(480) 460
Manganese	Mn'' (green)	77	MnO	650–575
	Mn'' (red)	48	$MnCO_3$, etc.	(580–540)
	Mn'''	0.1	$Li(Al, Mn)(SiO_3)_2$	560–520
Mercury	Hg''	86	HgS	610 590
Neodymium	Nd'''	0.5–15.0	Various; see tables	675 620 580 570 530 520 510
	Nd'''	0.005–0.5	Various; see tables	585 (525)
Praseodymium	Pr'''	0.5–15.0	Various; see tables	590 485 470 445
Samarium	Sm'''	1	$(Y, Sm)PO_4$, etc.	555 485
Uranium	U^{iv}	0.1–1.5	$(Zr, U)SiO_4$	685 660 650 620 590 560 535 510 485 460
	U^{vi}	30–50	(UO_2)-Ca salts	(550) (535) 515 500 485 470 455 445
	U^{vi}	35–55	(UO_2)-Cu salts	500 485 470 455 445
Vanadium	V''' (red)	0.01–0.05	$(Mg, Fe)_3(Al, V)_2(SiO_4)_3$	(530–520) 510–495

SMITHSONIAN MISCELLANEOUS COLLECTIONS
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EXPLORATIONS AND FIELD-WORK OF THE SMITHSONIAN INSTITUTION IN 1914

(With One Plate)

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EXPLORATIONS AND FIELD-WORK OF THE SMITHSONIAN INSTITUTION IN 1914

(WITH ONE PLATE)

During the year 1914 explorations and field-work were continued in various parts of the world under the direction or with the cooperation of the Smithsonian Institution. The more important are here reviewed, chiefly in the words of the participants therein. They include geological, zoological, botanical, anthropological, and astrophysical lines of investigation.

Three government branches of the Institution are represented in this report: the National Museum, although having no funds set aside for this purpose, avails itself wherever possible of opportunities to engage in natural history investigations and to add to its collections; the Bureau of American Ethnology is occupied largely with field-work among the Indians themselves, the annual report of that Bureau covering this work in detail; and the Astrophysical Observatory, in connection with its regular work of studying the physical properties of the sun and their effects on the earth, undertakes expeditions in this country and abroad for purposes of observation and investigation.

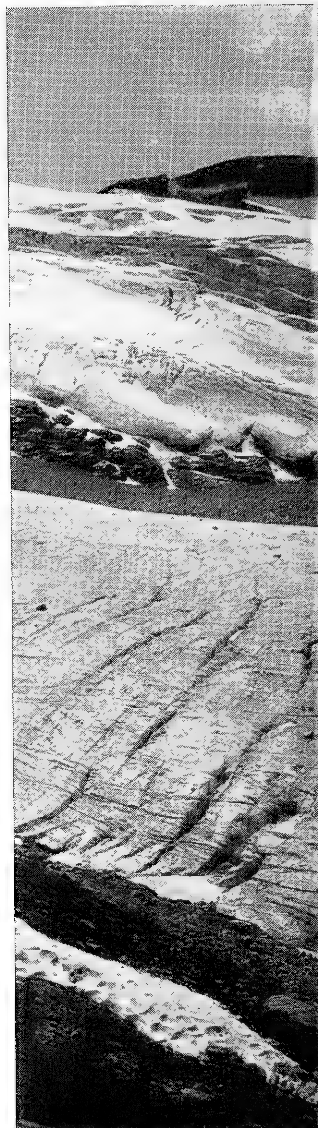
These various lines of field-work have tended to increase knowledge in the sciences and have added much valuable material to the collections of the National Museum and the Bureau of American Ethnology. The Institution was prevented from participating in many other expeditions only by its limited funds.

GEOLOGICAL EXPLORATIONS IN THE ROCKY MOUNTAINS

In continuation of his previous geological researches in the Rocky Mountains of Canada and Montana, Dr. Charles D. Walcott, Secretary of the Smithsonian Institution, spent a week during the field season of 1914 at Glacier, British Columbia, where he assisted Mrs. Walcott (née Mary M. Vaux) in measuring the flow of the Illecillewaet and Asulkan glaciers, photographs of which are shown in plate 1 and text figures 1 and 2.

From Glacier, Dr. Walcott proceeded to White Sulphur Springs, Montana, for the purpose of studying the ancient sedimentary Pre-paleozoic rocks of the Big Belt Mountains. These explorations were made on the eastern and southern slopes of this range, and

Fig. 1.—View of Illecillewaet Glacier from the north, showing the lower cascading portion and the bare rocks at its foot, which have been uncovered by the melting back of the ice for several hundred feet during the past five years. Photograph by Mary Vaux Walcott.



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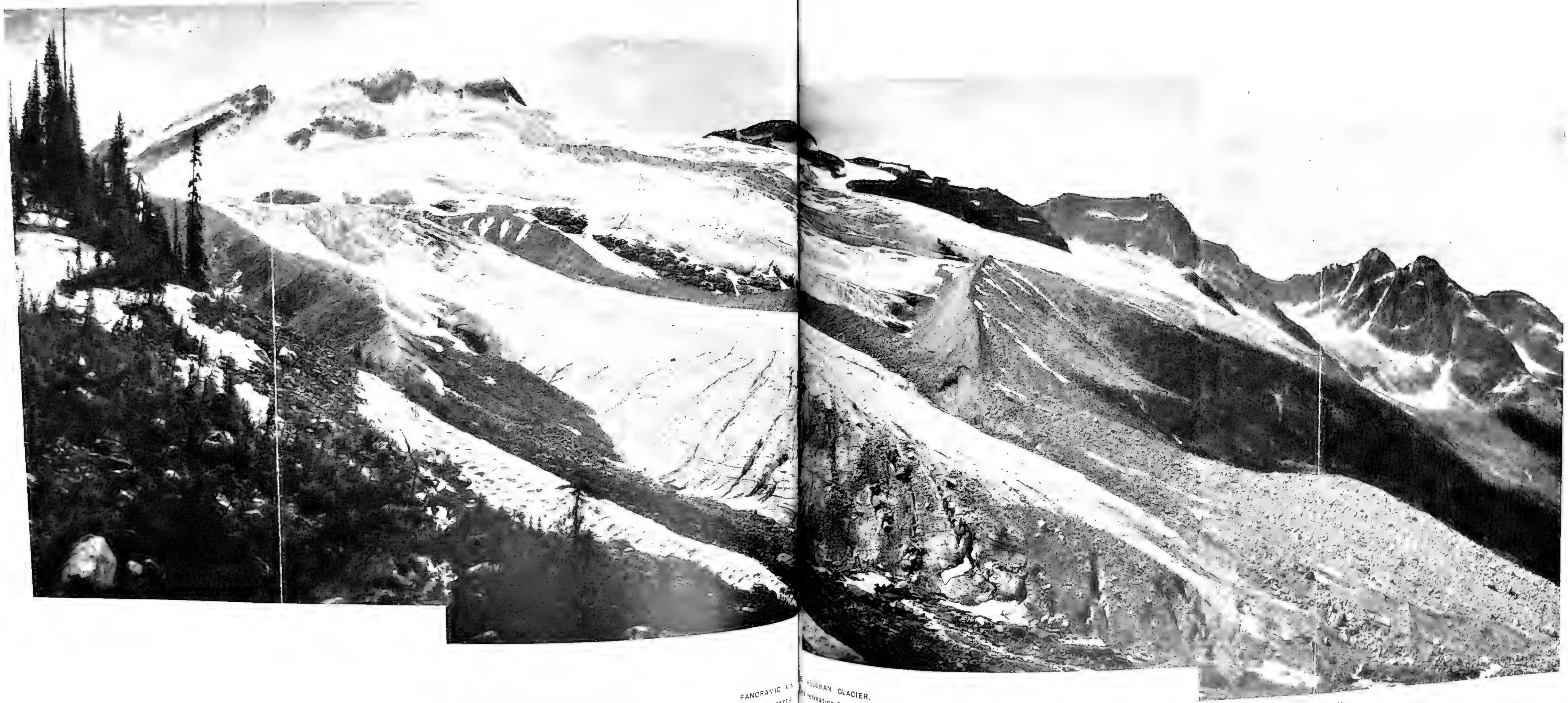

PANORAMIC VIEW OF THE ASULKAN GLACIER.

Showing the névé moraines and foot of the glacier. This is an unusual illustration of an entire glacier from its inception. Its retreating foot rests on the morainic débris that it has brought down from the mountain. Photograph by Mary Vaux Walcott.

FIG. 2.—View from the foot of Asulkan Glacier, looking down the valley toward Illecillewaet Valley, through which the Canadian Pacific Railway passes. A ridge of the Selkirks is shown in the distance. Photograph by Mary Vaux Walcott.

FIG. 3.—Hard sandstones which rest on the granite at the base of the Belt Mountain rocks. These sandstones form cliffs along the canyon, about five miles above Neihart, Montana. Photograph by Walcott.

FIG. 4.—Slaty shales in which the Prepaleozoic crustacean fossils were found near the mouth of Deep Creek Canyon, Big Belt Mountains, 16 miles east of Townsend, Montana. Photograph by Walcott.

FIG. 5.—Vertical layers of hard sandstone that occur in the formation beneath the shales, illustrated by fig. 4, and above the limestones carrying the algal remains that occur higher up in Deep Creek Canyon. Photograph by Walcott.

then extended to the south on the Gallatin, Madison, and Jefferson rivers.

It was found that the Prepaleozoic sedimentary rocks were exposed by the uplift of the granite mass forming the summit of Mount

FIG. 6.—Conglomerate in the sandstones illustrated by fig. 5, where there are boulders and pebbles derived from the limestones beneath. This indicates that the limestones were raised above the surface of the water, so that they were broken up by weathering, and fragments of them carried by streams into the near-by lake and embedded in the sand. Photograph by Walcott.

Edith of the Big Belts, in such a way that the thickness of the sandstones, limestones, and shales could be readily measured in the numerous sections exposed in the canyons worn by waters descend-

Fig. 7.—A cliff formed by hard layers of sandstone with thin layers of shale between. These rocks occur above the shales illustrated in fig. 4. Photograph by Walcott.

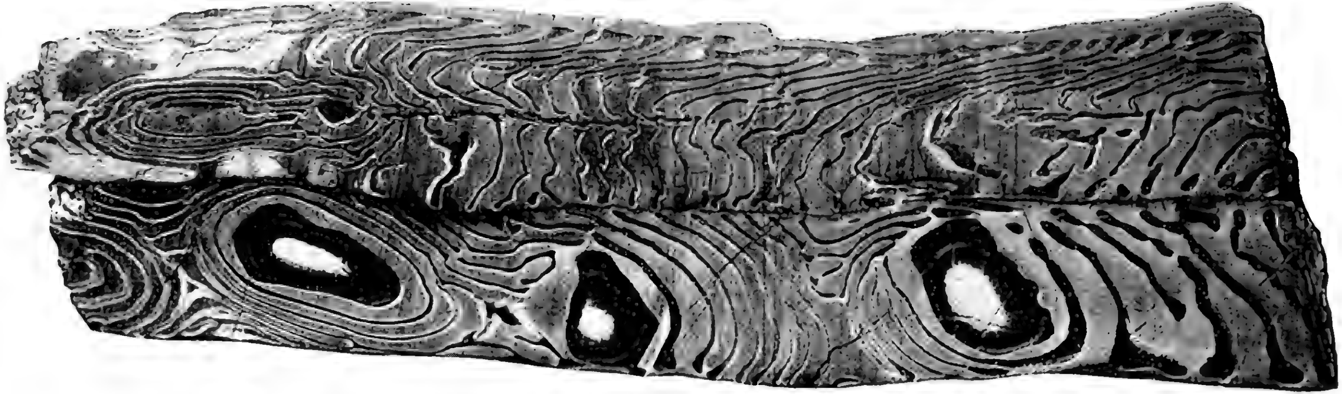

FIG. 8.—Curious pattern in limestones supposed to result from algal deposits.

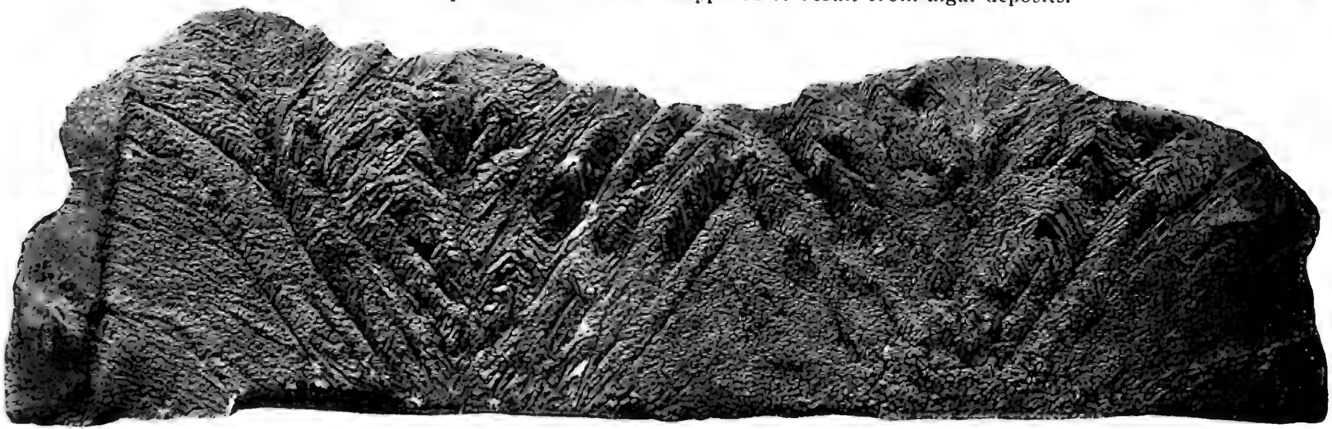

FIG. 9.—Etched section through the center of a double concretionary-like form which may have been influenced in its growth by algal deposits, and which contains numerous fossil bacterial remains.

ing from the higher points to the valley surrounding the range. Nearly five miles in thickness of rock were measured, and in the limestone belts reefs of fossil algal remains were studied and large collections made with the assistance of Mrs. Walcott and Charles E. Resser and sent on to Washington.

It was found that the algal remains were deposited very much in the same manner as those that are now being deposited in many fresh-water lakes, and that many of the forms had a surprising

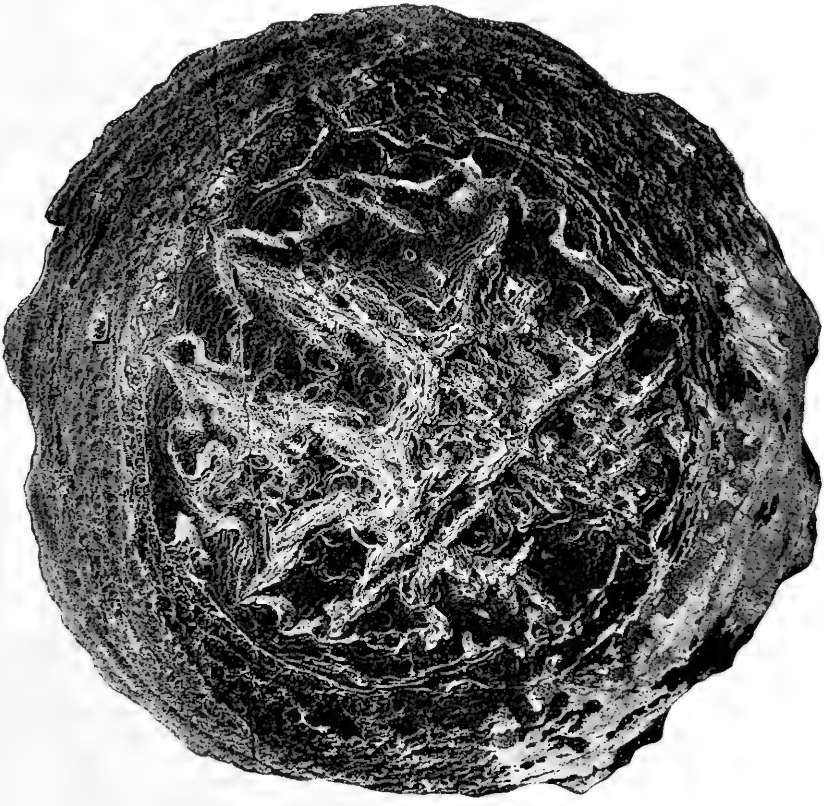

FIG. 10.—Upper surface of a lens-shaped concretionary-like form which resembles some of the siliceous deposits of the Yellowstone Park hot springs. This form has been named *Galiatinia pertexa*. Numerous cells such as occur in the Blue-green algæ have been found in thin sections of this type of supposed algal deposit.

similarity to those being deposited in the thermal springs and pools of the Yellowstone National Park.

In the lower portion of Deep Creek Canyon southeast of the city of Helena, a deposit of siliceous shale was examined, where some years ago Dr. Walcott discovered the remains of crab-like animals

suggesting in form the fresh-water cray fishes found in the streams and ponds all over the world.

These fossils are the oldest animal remains now known, and the algal deposits which occur at intervals for several thousand feet below the shales containing the crustaceans, are the oldest authentic vegetable remains. It is also most interesting that two types of bacteria have been found in a fossil state in the rock in association with the algal remains.

On the north side of the Gallatin River, two very rich beds of algal remains were found, many of which, on account of the fossil being silicified and embedded in a softer limestone, were weathered out in relief, as shown by figure 8.

FIG. 11.—Calvert Cliffs, Chesapeake Bay, Maryland, showing outcrop of Miocene bryozoan beds. Photograph by Bassler.

STUDIES IN COASTAL PLAIN STRATIGRAPHY AND PALEONTOLOGY

Dr. R. S. Bassler, curator of paleontology, U. S. National Museum, was engaged during the month of June, 1914, in a study of the Tertiary paleontology and stratigraphy of the Atlantic Coast Plain with special reference to the bryozoan faunas. This work was for the purpose of making further collections and of determining the stratigraphic relations of these bryozoan faunas for publication in the Monograph of North American Early Tertiary Bryozoa, now in course of completion by Ferdinand Canu of Versailles, France, and Dr. Bassler.

Starting at Chesapeake Beach, Maryland, and continuing southward through Virginia, North Carolina, South Carolina, Georgia, and Alabama, all the classic localities were visited, as well as many not so well known. The celebrated Calvert cliffs along Chesapeake Bay yielded a rich Miocene fauna and here many specimens were easily secured by searching the débris along the beach as shown in the accompanying photograph (fig. 11).

At Wilmington, North Carolina, an especially fine lot of material suitable for biological studies was collected from the city rock quarry, through the generous cooperation of the contractor in charge of some convict laborers. In South Carolina, the curator was taken through the swamps to the fossil localities by Mr. Earle Sloan, former

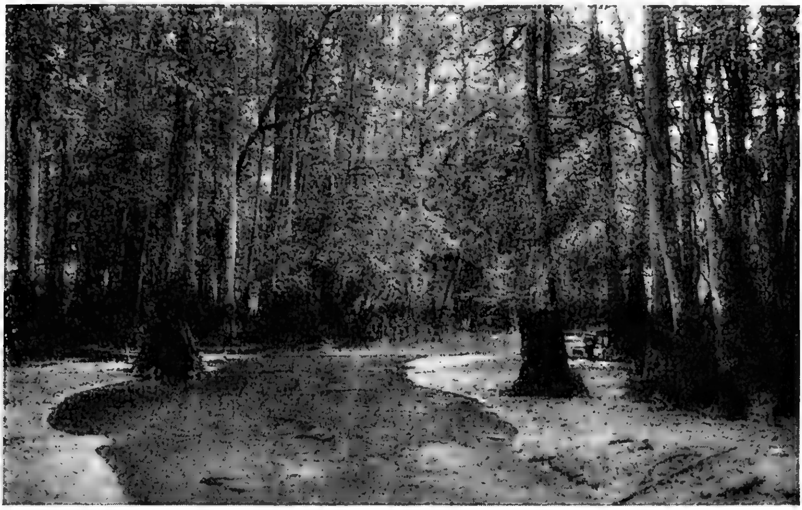

FIG. 12.—Cypress swamp, Santee River basin, South Carolina. Photograph by Bassler.

State geologist, without whose expert knowledge of the region little could have been accomplished. Here in many cases the rock exposures consisted of nothing but small outcrops brought to the surface by the "knees" of the cypress trees (fig. 12), but weathering of the hard rock had been so complete that many specimens could be had free of surrounding matrix. In Georgia and Alabama an abundance of material collected carefully with regard to its geologic position was secured and the stratigraphic position of several hitherto unplaced faunas was determined. The results of this field work from both the paleontologic and stratigraphic standpoints were so satis-

factory that the completion of a monograph upon the subject is now assured.

EXPLORATIONS FOR FOSSIL ECHINODERMS IN WESTERN NEW YORK

The field explorations conducted under the supervision of Mr. Frank Springer, associate in paleontology in the U. S. National Museum, for the purpose of adding to the Springer collection of fossil echinoderms, were devoted mainly to careful work in the Silurian rocks exposed along the new Erie Canal in western New York. Here Mr. Springer's private collector, Frederick Braun, spent some weeks during the summer of 1914 searching especially the waste material thrown out in excavations for the canal. The most valuable specimens from this part of New York occur in the Rochester shales of Niagaran age, which weather rapidly into mud upon exposure to the elements. It was necessary, therefore, that the new outcrops exposed along the canal be examined at once if valuable returns were to be expected, and Mr. Braun was directed accordingly to concentrate his efforts upon this area. The results were highly satisfactory, as numerous specimens of crinoids and cystids were found, a number of them having, as is rarely the case, root, stem, and crown preserved. These specimens were prepared for exhibition during the fall of 1914 and form a valuable addition to Mr. Springer's unique collection of fossils.

FOSSIL COLLECTING AT THE CUMBERLAND CAVE DEPOSIT

In continuation of the work of the previous year in the Pleistocene cave deposit near Cumberland, Maryland, Mr. J. W. Gidley, assistant curator of fossil mammals, again visited this locality in May and June of 1914. This expedition was highly successful and has added over 400 specimens to the fine collection from this deposit, including a good skeleton of the large extinct peccary, a partial skeleton of the wolverine, and several nearly complete skulls of these and other species. Among the latter are five good skulls of extinct species of the black bear and eight skulls, in more or less good state of preservation, of the extinct peccary.

Some new forms not before found in this deposit were obtained, the most important being a new species of badger and a second type of extinct peccary known as *Mylohyus*. The collection of the 1914 expedition far exceeds, both in numbers and quality of specimens, those previously taken from this deposit. The cubic space excavated was also much greater than before, yet at the end of the season's work the deposit showed no signs of immediate exhaustion of fossil-

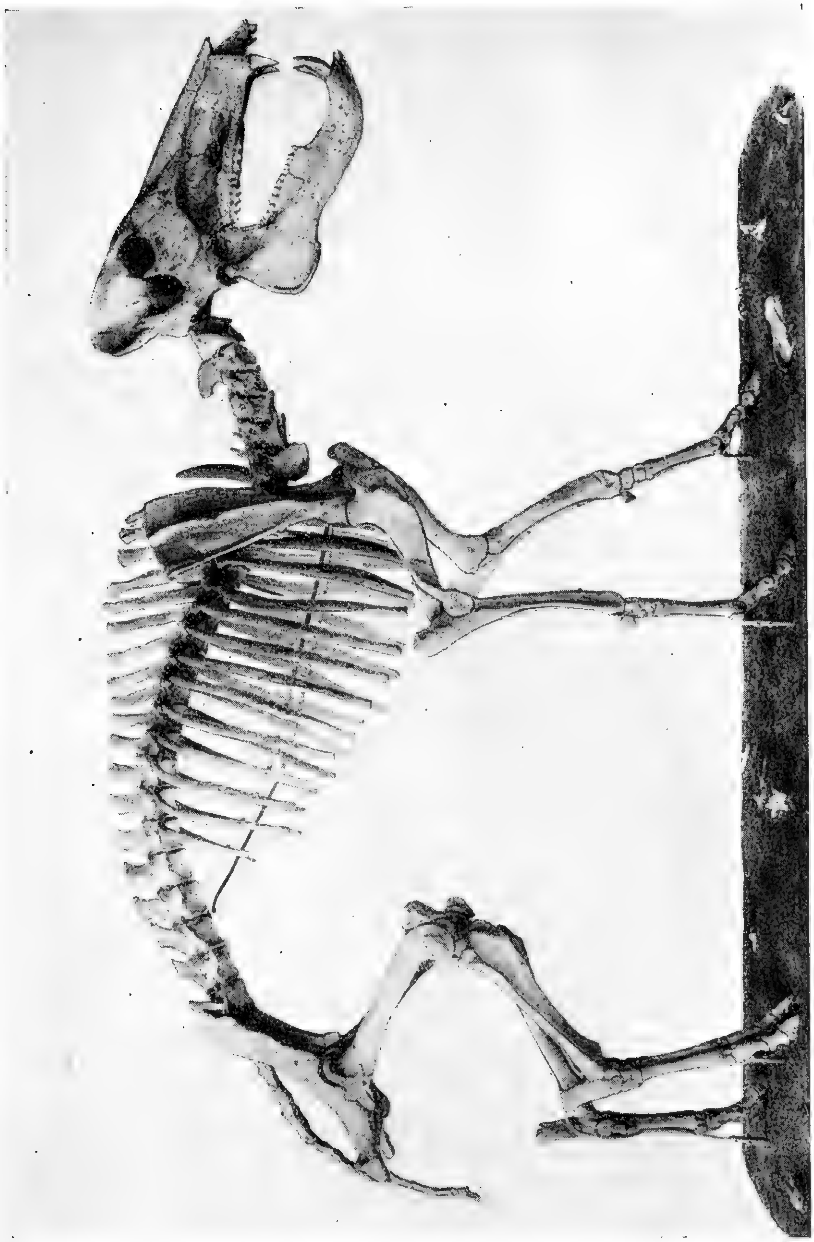

FIG. 13.—Skeleton of extinct Peccary from the Cumberland cave deposit. About 1/8 natural size.

Fig. 14.—View in railroad cut showing excavation made by U. S. National Museum party, 1914 expedition. Photograph by Armbruster.

bearing material, and it is expected that this work will be further continued during the coming summer.

In addition to the fossil bearing cave clays and breccias filling the old cavern, it was necessary to remove several tons of overhanging stalactitic rock and anciently fallen blocks of limestone. This added to the more cave-like appearance of the opening, as may be seen by comparing figure 14 herein with figure 18[1] published in last year's account of the work at Cumberland.

The results of the work of the 1914 expedition have greatly increased the possibility of accurate determinations of the fauna represented in this very interesting cave deposit and it is hoped the

FIG. 15.—Bad Land exposures near the mouth of Dog Creek, Montana. Photograph by U. S. Geological Survey (T. W. Stanton).

proposed further exploration will furnish added material of even greater importance.

HUNTING VERTEBRATE FOSSILS IN MONTANA

During the summer of 1914 Mr. Charles W. Gilmore, assistant curator of fossil reptiles in the National Museum, spent three weeks searching for fossil vertebrate remains in the Judith River formation in north central Montana.

By arrangement with the U. S. Geological Survey Mr. Gilmore worked in cooperation with one of their field parties. From their camp as a base of operations he conducted an exploration of the exposures along Dog and Birch creeks, near Judith post office, in

[1] Smithsonian Misc. Coll., Vol. 63, No. 8, 1914, p. 16.

the hope of collecting identifiable material to supplement the fragmentary fossil specimens secured by earlier expeditions. Abundant evidence of the presence of fossil remains was found, but much of the material was fragmentary and only a few specimens were shipped

FIG. 16.—Judith River and Claggett formations as exposed on Dog Creek, Montana. Bird remains found at base of cliff in middle distance. Photograph by Gilmore.

to Washington. From a paleontological standpoint the most noteworthy discovery was the fragmentary remains of a fossil bird related to *Hesperornis* found by Dr. T. W. Stanton on Dog Creek (fig. 16). It came from practically the same locality as the type of *Coniornis altus* Marsh, and is of importance as showing these bird

remains as occurring in the upper part of the Claggett formation, whereas heretofore it was thought that *Coniornis* had come from the lower part of the Judith River formation.

Incidental to this paleontological work a collection of Indian skeletons was obtained for the National Museum. These remains, consisting of parts of eleven individuals, were found in shallow graves in the crevices of a large block of Eagle sandstone that had been faulted up and which forms a conspicuous landmark in the valley just above the mouth of Dog Creek. A picture of this rock is shown in figure 15.

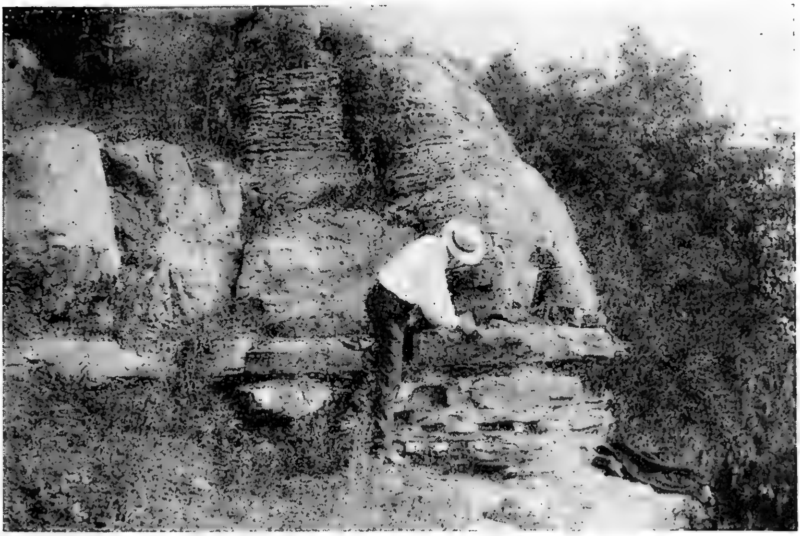

FIG. 17.—Unconformity between Lower Chazyan (Stones River) and Lower Black River (Lowville) strata at Columbia, Tenn. Dr. Ulrich is pointing to the undulating line which lies one to three inches below the top of the ledge indicated. Photograph by Bassler.

STRATIGRAPHIC STUDIES IN CENTRAL TENNESSEE

Dr. E. O. Ulrich, associate in paleontology, and R. S. Bassler, U. S. National Museum, were engaged for several weeks during the summer of 1914 in a study of debated points in the stratigraphy of the Central Basin of Tennessee under the joint auspices of the U. S. Geological Survey and the U. S. National Museum. The particular objects of the work were: first, to determine accurately the division line between the Chazyan and Black River groups, and second, to secure additional information on the black shale problem.

The well known marble beds of east Tennessee and associated shales and sandstones of Upper Chazyan age with a thickness of over 3,000 feet have never been found in central Tennessee, or in fact in any area west of the Appalachian Valley. The first problem was therefore to determine either the corresponding rocks in the more western areas or, if such strata were wanting, to discover the unconformity representing this great thickness. After some days of careful stratigraphic work it was learned that the Lower Chazyan or Stones River rocks of central Tennessee are succeeded directly by the lowest Black River or Lowville formation. In other words,

Fig. 18.—Exposure of black shale and underlying Silurian strata at Bakers, Tenn. Photograph by Bassler.

all of the Upper Chazyan rocks are wanting entirely, and central Tennessee therefore was presumably a land area during the time of deposition of the celebrated east Tennessee marbles. The unconformity between the two groups of strata is shown in figure 17, where it may be seen as an undulating line in a single ledge of limestone.

The second problem entailed further work on the determination of the age of the widespread Chattanooga black shale, which previously had been considered to be middle to late Devonian. In recent years this determination had been questioned and facts had accumulated showing it to be of younger age. Two features of considerable

significance in this problem were the discoveries in northern Tennessee, where the shale is well exposed, as shown in figure 18, that (1) this black shale passes without a discernible break into the overlying Mississippian (Kinderhook) shales, and (2) that the fossils of this overlying shale are of late instead of early Kinderhook age. As a result of this work good collections of several well preserved faunas were added to the Museum collection.

GEOLOGY OF CERTAIN AREAS IN EASTERN PENNSYLVANIA

Dr. Edgar T. Wherry, assistant curator of the division of mineralogy and petrology, by arrangement with the U. S. Geological Survey, spent a month during the summer of 1914 in the study of the Pre-Cambrian, Cambrian, Ordovician, and Triassic formations of the Reading and Allentown quadrangles in eastern Pennsylvania. In the former area particular attention was directed toward the lithologic character and fossil content of the Conococheague and Beekmantown limestones, and the mapping of these and other post-Cambrian formations, which had been begun the previous season, was practically completed.

In the Allentown region brief visits were paid to several localities to secure data for the text of the Allentown-Easton folio, which is in course of preparation. The criteria for recognition of the various Pre-Cambrian formations, especially the metamorphosed sediments, were worked out in detail, and sections of the Triassic and Paleozoic beds measured.

GEOLOGICAL STUDIES IN NEW YORK STATE

Dr. J. C. Martin, assistant curator of geology, has spent some time completing minor details in the preparation of a report on "The Pre-Cambrian Rocks of the Canton, N. Y., Quadrangle," to be published by the New York Geological Survey.

The examination of this area involved the working out of structural and genetic problems of a high degree of complexity, the solution of which demanded methods of great accuracy and detail.

Among the results obtained may be mentioned, particularly, the determination of the close analogy between tectonic elements of widely differing degrees of magnitude, and the recognition of a type of major isoclinal folding with steep-dipping axes, paralleled, so far as known, only by occurrences in Sweden. In addition there were obtained many new data with reference to the origin and relations of multiple injection gneisses of more than one generation,

as well as the sequence of acid and basic igneous rocks and the complex interrelations of extensive garnet gneisses, amphibolites, and other Grenville and post-Grenville crystalline formations.

EXPEDITION TO BORNEO AND CELEBES

Mr. H. C. Raven, who, through the generosity of Dr. W. L. Abbott, has been working in Borneo since the summer of 1912,

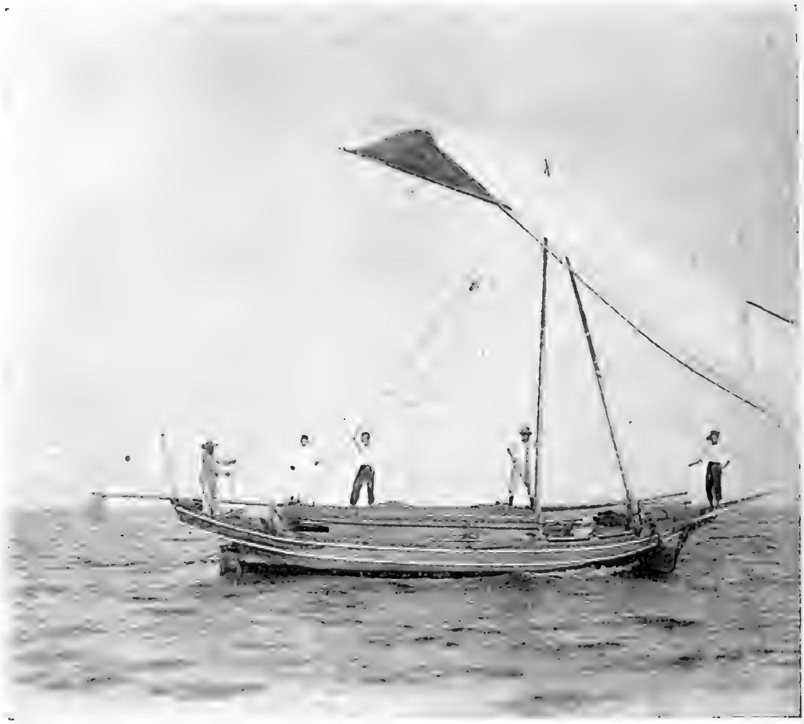

FIG. 19.—The "Bintang Kumala," used by Mr. Raven in Borneo from July, 1912 to July, 1914. Photograph by Raven.

continued his explorations, with Samarinda, Dutch East Borneo, as headquarters. During the early part of the year he worked on the coast north of Samarinda, and later he ascended the Mahakam River. The results were satisfactory, though the region of the upper Mahakam proved somewhat disappointing on account of the practical extermination by the natives of all mammals large enough to be used as food. About the middle of July Mr. Raven finished his Bornean exploration and crossed the Macassar Strait to the Island

of Celebes, where he intends to remain for an indefinite period. This change of base was not so simple a matter as might be supposed, as is shown by the following passage from a letter dated at Tanjong Lango, Celebes, August 28, 1914:

As I wrote before, when I returned from the interior of Borneo to Samarinda, I had to have my boat, the "Bintang Kumala," hauled out. It needed repairs and drying after having been in the water constantly for two years or more. The Assistant Resident stationed at Samarinda at this time went up

FIG. 20.—Camp at Karang Tigau, Celebes, August, 1914. Photograph by Raven.

along the coast to Beraoe and I asked him to bring me two or three sea-faring natives to act as a crew to cross with me to Celebes. He was unable to get them. I tried, but could find no Bajans or Soeloes who would go, but finally found, near Samarinda, three Bugginese who claimed they could sail. So when the boat was ready we started, and to my great disappointment I found my crew entirely incapable, running the boat ashore before we had gotten fairly started. There was nothing to do but to return to Samarinda. I thought of having the boat either towed or lifted across to Donggala by the steamer making that run at intervals of two weeks; this I found would cost more than one hundred and fifty dollars, and after crossing I would stand a big chance of having the same trouble in getting a reliable crew. Just at that time a small two-master schooner came into Samarinda and my attention was called to it

by a European who considered my boat unsafe to cross in. I had a look at the schooner and found it to be strongly built and in pretty good condition, 54 feet long and 12 feet beam, drawing about 4 feet of water. It is made entirely of iron-wood.

After considering, I decided the best plan would be to buy the schooner, and as the owner was willing to sell, we came to terms. He bought my boat for three hundred and fifty guilders and I was to buy the schooner for thirteen hundred and fifty guilders, but found that I could not own and sail a boat under the Dutch flag unless I had been holder of citizen's papers for a full

FIG. 21.—Beraoe Malays at Maratua Island, southeast Borneo. Photograph by Raven.

year. According to the Dutch law, coasting under a foreign flag is prohibited. Thus my only way was to make a contract of "Bond Loan," stating that I had loaned thirteen hundred and fifty guilders to Hadji Mohamad Arsad and as security he gives into my absolute custody his schooner, which he may redeem only during the thirteenth month after date by paying the sum of thirteen hundred and fifty guilders and must accept the schooner in any condition in which she may be at that time. He can never claim damages, inasmuch as the loan equals the value of the schooner; also that if Hadji Mohamad Arsad breaks the contract and takes back the schooner before the end of the twelve months after date (July 4, 1914), he must pay not only the sum of the loan

but also a fine of five hundred guilders. To find a crew for this boat was not difficult, and she is far better to handle than the smaller one and no more expensive to man, probably cheaper. Having crossed to Celebes in this boat, I should not care to do it in the smaller one, for Macassar Strait is 140 miles wide and over a thousand fathoms deep. A current running against the wind sometimes makes bad weather. Nearly all the coast of Celebes is rocky, with deep water close in to shore, so that in case of storm we sometimes have to run out to sea rather than chance going on rocks. In such cases it is exceedingly difficult in a small boat to keep anything dry.

FIG. 22.—Dyak woman, Segah River, Borneo. Note ear ornaments and tattooing on thighs. Tattooing is difficult to photograph on account of its coloring. Photograph by Raven.

On reaching Celebes Mr. Raven immediately began his field work, with what success may be inferred from further passages from the letter of August 28.

The country here is a great contrast to that of Borneo and mammal life not nearly so plentiful. There is a mining company located at Paleleh working gold, and they have cut trails back into the jungle. There are several Europeans and they allowed me to use their trails. I went inland about four or five miles over the mountains and made camp at the edge of the Paleleh River,

which is a small brook and at this season nearly dry, with steep mountains or hills on all sides.

My traps I placed not far from the river, which at this dry season should be as good as any place. Nearly everywhere the shore is planted with cocoanuts and oftentimes clearings are made on the hill slopes, but inland the original forest remains unmolested, though it is not open forest like that of eastern Borneo. There is much underbrush, composed principally of a variety of almost worthless rattan.

Thus far I have collected specimens of Babirusa [a pig with peculiar erect tusks curved backward above forehead at extremities], two females with

Fig. 23.—Two attitudes of Pangolin. Length of animal: head and body, 26 inches; tail, 22 inches. Mahakam River, Borneo. Photograph by Raven.

skins and some fine skulls of males. Also a peculiar black pig with hard cartilaginous conical nodules on its nose and hard jowel patches; a marsupial and two species of squirrels. I have also seen a reddish squirrel running on the ground, but have not gotten one; also I have seen a small carnivore. Of rats I have six or seven species, and possibly there are more. I have also some bats. The ants do not seem to destroy as many rats here as in Borneo; this will prove a great advantage in collecting.

According to natives, Sapi-utan [a dwarf buffalo peculiar to Celebes] and Rusa [deer] in certain localities are abundant, though I have yet seen none. The natives also say there are many wild water-buffalo which have escaped from captivity years ago.

Reptiles appear to be common and the miners at Paleleh killed a python which they say *measured* 10 meters.

Black macacus monkeys are generally common and at a distance look like black dogs. About the edges of the forest I have seen many birds, but in the deep forest I have seen very few.

Photographs I can probably send via Gorontalo. The chief difficulty in making pictures here is the dirty, warm water.

No specimens from Celebes have yet been received in Washington; but all the Bornean material is at hand, forming a very important addition to the National Museum collection. It includes 310

FIG. 24.—Gymnura, an animal related to the European hedgehog, though its body is covered with coarse hair instead of spines. Length: head and body, 14 inches; tail, 11½ inches. Samarinda, Borneo. Photograph by Raven.

mammals taken in 1914, making total of 1,613; and 261 birds taken in 1914, making total of 1,440.

Some of the photographs alluded to by Mr. Raven are here reproduced.

EXPEDITIONS TO THE FAR EAST

Mr. Arthur de C. Sowerby has continued his explorations in Manchuria and northeastern China. Interesting specimens received from him are two wapiti bucks and a roe deer. A recent letter announces the capture of two bears and a peculiar rabbit.

Mr. Copley Amory, Jr., a collaborator of the National Museum, joined the party accompanying Captain J. Koren to the northeast coast of Siberia. This party sailed from Seattle about June 25, and was last heard from at Nome, Alaska, on July 19. It is Mr. Amory's intention to explore such territory as may be practicable from Nijni Kolymsk as a winter base. He will give special attention to mammals and birds. Figure 25 is from a photograph of Captain Koren's boat.

FIG. 25.—Captain Koren's vessel which took exploring party to Siberia.

THE "TOMAS BARRERA" EXPEDITION IN WESTERN CUBA

During the months of May and June, 1914, an expedition under the joint auspices of the Smithsonian Institution and the Cuban Government was made to Cape San Antonio and the Colorados Reefs of northwestern Cuba. Through the great generosity of Senor Raoul Mediavilla of Havana, the use of the large and well-equipped schooner "Tomas Barrera" was given the expedition free of all cost of charter. This schooner, of the class locally known as a "Vivero," contains a large well or tank admitting sea water, a feature which proved of greatest value for stowage of living specimens. A carefully selected crew, familiar with the intricate channels of the reefs, was also provided by Senor Mediavilla. Besides the schooner, two power launches were also taken, one especially equipped for dredging in moderate depths.

FIG. 26.—The "Tomas Barrera" in Havana Harbor.

FIG. 27.—Setting traps for fish and crustaceans off Cape Cajon.

Fig. 28.—The Patron of the "Tomas Barrera" with a huge sponge, only a portion of which appears above water, secured by diving. One of the dredges used by the party is shown hanging over the edge of the launch.

Fig. 29.—Henderson and Greenlaw collecting Cerions.

FIG. 30.—The big land Crab of Cuba.

FIG. 31.—Track for charcoal burners' carts, extending miles into the interior at Cape San Antonio, along which were obtained hundreds of specimens of all kinds of animals.

The main object of the expedition was to make as complete as possible a biological survey of the waters of western Cuba, especially of the extensive Colorados Reefs, heretofore wholly unexplored by naturalists, and to obtain fine specimens for the exhibition series of the National Museum. Another purpose of the visit to this region was to investigate closely the fauna of certain high mountains of the northern ranges of the *Sierra de los Organos* to gather material from those inaccessible localities. The chief interest of the Cuban Government was a study of food-fish life of the reefs, and to that end

FIG. 32.—Bartsch collecting the rare landshell, *Urocoptis dautzenbergiana,* of which several hundred were obtained in the space shown in the photograph.

Sr. Lesmes of the Cuban Fish Commission was detailed by President Menocal to accompany the party.

Careful preparation was made for intensive field work and a full equipment of dredges, traps, submarine electric lights, chemicals for stupefying marine animals, etc., was taken.

Besides extensive dredging operations carried on daily, shore parties visited the two great mountains, Pan de Guajaibon and Pan de Azucar, and also spent some time in the Viñales region, about Guane, and in the low-lying country about La Fe, and finally spent several days collecting in the heavily forested region about Cape San Antonio. From these shore stations an immense number of specimens were collected, including many species new to science.

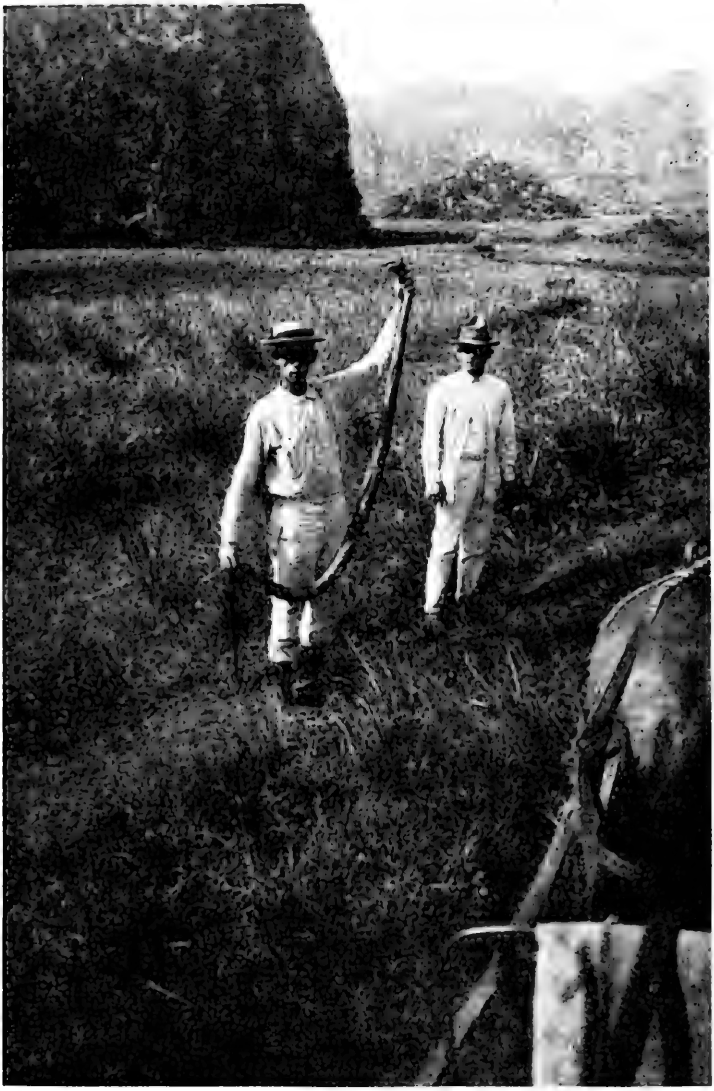

FIG. 33.—The Cuban Maja (*Epicrates angulifer* Bibron). Frequently met with while hunting landshells in the mountain country.

FIG. 34.—River at La Mulata on the trail to Mt. Guajaibon, where fresh-water animals of various kinds were collected. Henderson and Clapp at water's edge, and Rodrigues at right.

FIG. 35.—Typical jungle scene and a favorite place for fresh-water mollusks.

FIG. 36.—Cove of Delight in the Viñales Range. A famous collecting ground for land mollusks.

The expedition met with signal success and returned a great quantity of interesting material to the Museum, which is now in the hands of specialists for final report. Splendid collections in all of the phyla of marine organisms, including protozoa, sponges, corals,

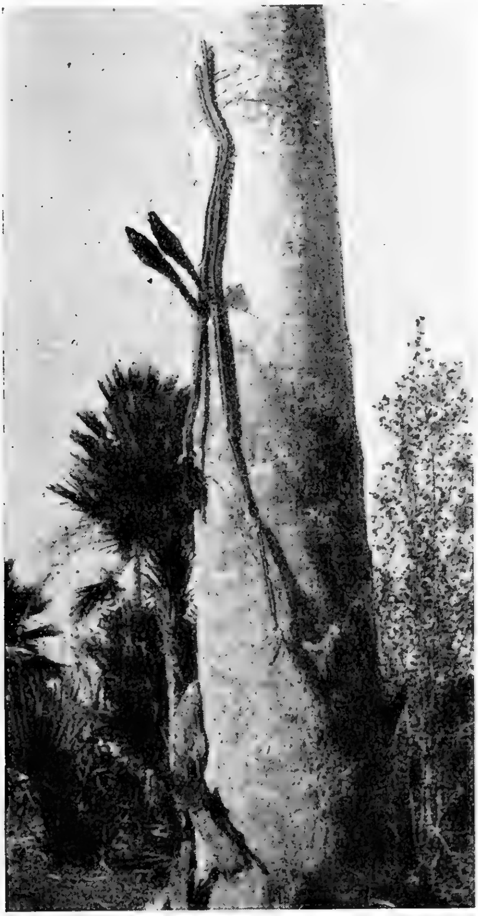

FIG. 37.—A Cuban cactus in flower.

gorgonians and medusæ and other cœlenterates, annulates, echinoderms, crustaceans and mollusks, were made. The usual hydrographic data were also carefully kept, and bottom and water samples were taken at the various stations. Whenever possible collections of fresh water organisms were secured. The wonderful development of molluscan life furnished by far the greater part of our

catch, though the efforts of the expedition were by no means solely devoted to this end. The vertebrates, as well as the lower organisms, added materially to our catch. Among plants, special attention was given to the cacti, of which a number of very interesting forms were secured. A general account of the expedition, "The Log of the Tomas Barrera," by Mr. Henderson, is almost completed, and detailed reports on results of the expedition, by various specialists, are to follow.

The party consisted of Mr. John B. Henderson, member of the Board of Regents of the Smithsonian Institution; Dr. Paul Bartsch, curator of marine invertebrates, U. S. National Museum; Dr. Carlos de la Torre of the University of Havana; Mr. George H. Clapp of Pittsburgh, Pa.; Mr. Charles T. Simpson of Little Rivers, Fla., formerly of the Museum staff; and of Mr. Gill, the Museum colorist, and Mr. Victor Rodrigues, preparator at the University of Havana.

It is expected that this expedition to western Cuba will be followed by a series of similar explorations in other parts of the Antillean regions looking primarily to the enrichment of the Museum collection in the fauna of the West Indies, in order that we may gain a clearer understanding of the faunas and faunal relationship of the West Indies.

EXPERIMENTS WITH CERIONS IN THE FLORIDA KEYS

Brief accounts have been published in previous Smithsonian exploration pamphlets [1] of the Bahama Cerion colonies planted on the Florida Keys by Dr. Paul Bartsch of the U. S. National Museum, under the auspices of the Carnegie Institution of Washington. As regards the development of the new generation of these shells in a new environment, it was stated last year that "judging from the young collected which were born on these keys (fig. 38), the first generation will be like the parent generation, unless decided changes should take place in the later whorls, which have not as yet been developed." On Dr. Bartsch's visit to the colonies in April, 1914, however, adult specimens of the new generation were found at several localities, and these fully developed adults enable him to state that a decided change has taken place. So pronounced are the departures from the parent generation that the specimens would undoubtedly be considered by one unfamiliar with the history of the material as distinct species and not closely related to the parent

[1] Smithsonian Misc. Coll., Vol. 60, No. 30, pp. 58-62; Vol. 63, No. 8, pp. 27-30.

FIG. 38.—Young Cerions grown on Loggerhead Key, Tortugas, Florida.

stock. Also the first generation shows a wider range of variation than the parents.

FIG. 39.—Bahama Cerions on Duck Key, Florida.

This departure from the parent generation is shown in the shape, coloration, and sculpture of the shells (fig. 40). The tendency of the whole lot is toward elongation, and toward the attenuating and

rounding of the base. There is one type of variation in which the ribs are almost obsolete and very widely spaced. Another is darker and narrower, and the ribs are much more crowded together. All these various modifications in the new generation show that the

b *a* *c*

FIG. 40.—*a,* A typical planted specimen; *b* and *c,* two changes shown in the first generation of Florida-grown specimens.

FIG. 41.—Man-o'-war birds suspended on motionless wing on upthrust of air above southeast corner of Fort Jefferson, Tortugas, Florida.

somaplasm in the Cerions experimented with has been affected by the new environment in which they were developed.

Further even more interesting results bearing on heredity and environment are expected from the continuation of Dr. Bartsch's studies with the Cerions. A full account of the work so far done and the results obtained will shortly be published by the Carnegie Institution of Washington.

During Dr. Bartsch's trip in 1913, a record was kept of the birds observed on the Florida Keys, and as this list proved of considerable interest to ornithologists, the observations were continued in 1914. Some 46 species were noted, including 19 not observed the previous year. A detailed account appears in the Year Book of the Carnegie Institution of Washington for 1914, pp. 192-194.

BIRD STUDIES IN ILLINOIS

Incidental to continued work on preparation of manuscript of the unpublished volumes of "Birds of North and Middle America" (Bulletin 50, U. S. National Museum), Mr. Robert Ridgway made a careful study of bird-life in southern Illinois, in order to compare present conditions with those existing half a century ago. The results of this investigation will be published in the May-June, 1915 number of "Bird-Lore." It was found that with a few exceptions the native birds have greatly decreased in numbers. At least three species (the passenger pigeon, wild turkey, and ruffed grouse) have totally disappeared from the region examined, while several others are on the verge of extermination. A few species, such as the crow blackbird (bronzed grackle) and blue jay, and perhaps the robin, are, apparently, as numerous as they were fifty years ago.

The principal causes which have brought about this greatly diminished bird-life are: (1) in the case of the game birds, relentless shooting; (2) greatly reduced breeding and shelter areas, through clearing of forests, cutting away of woody growths along roadsides and fence-lines and drainage of swampy or marshy areas; (3) introduction of the European house sparrow, which has increased to such an extent that it now outnumbers, even on the farms, all the smaller native birds combined, greatly reducing their food supply, and monopolizing the nesting sites of such species as the blue bird, purple martin, wrens, swallows, and other birds that nest in cavities or about buildings; (4) invasion of the woods and fields by homeless house cats, and destruction of eggs and young (often the parents also) of ground-nesting species by "self-hunting" bird dogs (setters and pointers); and, probably, (5) spraying of orchards.

CACTUS INVESTIGATIONS IN PERU, BOLIVIA, AND CHILE

Dr. J. N. Rose, associate in botany, U. S. National Museum (at present connected with the Carnegie Institution of Washington in the preparation of a monograph of the Cactaceæ of America), spent nearly six months in travel and field work on the west coast of South America during the summer and fall of 1914, visiting Peru, Bolivia, and Chile. He made collections on the coast at the following places: Paita, Pacasmayo, Saliverry, and Mollendo in Peru; Iquique, Antofagasta, Coquimbo, Los Vilos, Los Molles, and Valparaiso in Chile. As his chief work was to study and collect cacti, most of his time was spent in the interior deserts. A section was made through central Peru from Callao to Oroya, from sea level to the top of the Andes, the highest point reached being 15,665 feet. Cacti were found in the greatest abundance at an altitude of 5,000 to 7,500 feet; but the various species range from a few feet above sea-level to as high as 12,000 to 14,000 feet.

A second section was made across southern Peru, from Mollendo to Lake Titicaca via Arequipa. The highest point reached was 14,665 feet. Here also the cacti are found from near sea-level nearly to the top of the Andes; but the most remarkable display is on the hills surrounding Arequipa, at an altitude of from 7,000 to 8,500 feet. While the cacti are abundant in both these regions, they are, with only a few possible exceptions, quite distinct. Side trips were made from Arequipa to Juliaca and Cuzco, in Peru, and to La Paz, Oruro, and Comanche, in Bolivia.

On the pampa below Arequipa are found the famous crescent-shaped sand dunes. Each dune or pile of sand is distinct in itself, often separated some distance from any other dune, and occurring, too, on rocky ground devoid of other sand. The dunes are found on the high mesa some 5,250 feet above the sea. They form definite regular piles of sand, each presenting a front 10 to 100 feet wide and 5 to 20 feet high, nearly perpendicular, crescent shaped, and from the crescent-shaped ridge tapering back to the surface in the direction from which the wind blows. These piles of shifting sand go forward about 40 feet a year.

In Chile two sections were made into the interior—one from Antofagasta to Calama, and one from Valparaiso to Santiago. The first is through the rainless deserts of northern Chile, the whole region being practically devoid of all vegetation. The second is across central Chile, the hills and valleys of which are veritable

FIG. 42.—Showing the front of one of the crescent-shaped sand dunes characteristic of the high pampa between Mollendo and Arequipa, Peru. These dunes move forward about 40 feet a year.

Fig. 43.—A group of palms, *Jubaea spectabilis* H. B. K., common in the Chilean valleys north of Santiago. From the sap of this palm is made a delicious syrup, "Miel de Palma," much prized by the people of this region.

flower gardens, the hills often being a mass of yellow. Various trips were made in the central valley of Chile and one journey along the Longitudinal Railway of Chile extended from Caldera to Santiago. Special trips were made for certain rare plants like *Cereus castaneus,* first collected in 1862 and not since observed until found by Dr. Rose; and *Cactus horridus* and *Cactus Berteri,* described in 1833, but long since discarded by Cactus students. In the central valley of Chile is seen that beautiful palm, the only one native of Chile, *Jubaea spectabilis* H. B. K., which often forms forests of considerable extent. From this palm is made the "Miel de Palma" so much used as a syrup on ships and at hotels.

Dr. Rose made extensive shipments of living cacti. Most of the material is of species new to American collections and quite a number have not before been in cultivation, while some are new to science. In addition, formalin and herbarium material was obtained in abundance. His collection represents over 1,000 numbers, consisting not only of cacti, but ferns, grasses, mosses, marine algæ, parasitic fungi, and other miscellaneous groups which Dr. Rose believed would be of help to various specialists.

BOTANICAL EXPLORATIONS IN NEW MEXICO AND TEXAS

During August and September, 1914, Mr. Paul C. Standley of the division of plants of the National Museum and Mr. H. C. Bollman of the Smithsonian Institution spent nearly five weeks camping in northern New Mexico at the Brazos Canyon in Rio Arriba County. This locality is about 30 miles south of the Colorado line and about half way across the state. While the trip was a private undertaking primarily for vacation purposes, a representative collection of the plant life of the region was made.

The Brazos Canyon is a gorge through which the Rio Brazos, a tributary of the Chama River, runs for several miles. Near Tierra Amarilla, where it flows into the Chama, the Brazos is a broad stream, with only a moderately rapid current. As one follows up its course the stream gradually becomes more rapid, and the valley narrower. Eight or nine miles west of Tierra Amarilla there rises on the north side of the valley a high mesa, with an abrupt escarpment of naked reddish rocks, and one finally comes to a gigantic fissure in the escarpment from which the Brazos issues. Here, for several miles, the stream runs through a deep gorge, bounded by bare, perpendicular granitic walls from two to three thousand feet high, in places less than a hundred yards apart. This chasm is

similar to the Taltec Gorge, which receives so much attention from the tourists who travel over the line of the Denver and Rio Grande Railroad between Antonito and Durango, Colorado, and it is probably superior in size to that better known canyon. The Brazos, within its canyon, and for a couple of miles after leaving it, is a swift stream of considerable volume, rushing along over rapids or falling now

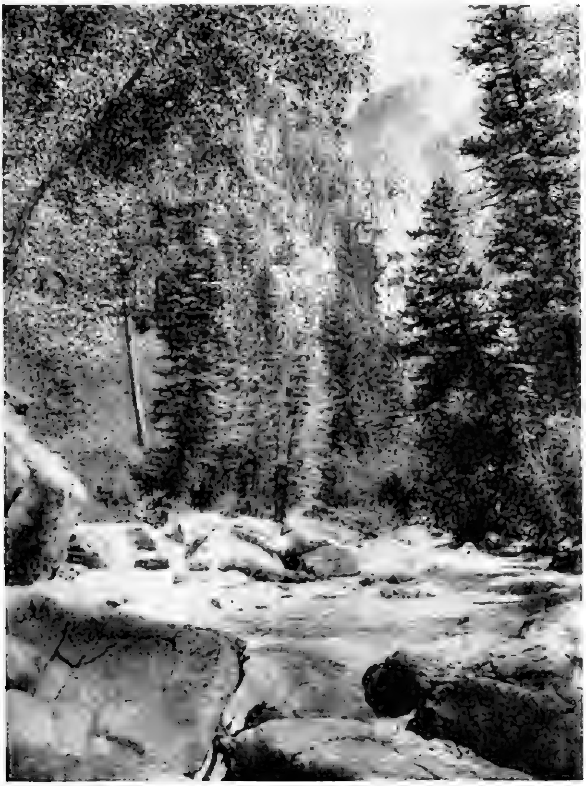

FIG. 44.—Along the Brazos, looking toward the Brazos Canyon. Photograph by Standley.

and then over great polished boulders into broad, deep, dark green pools. It is frequented by large numbers of trout, and for fishing is not excelled by any stream in the state, unless it may be the upper Pecos.

The surrounding country is well timbered, at least in the less accessible portions. The region being included in one of the old Spanish grants, it has been impossible to conserve it in one of the national forests, and most of the yellow pine at lower levels has

been removed. In the vicinity of the canyon, however, there is a moderately heavy growth of Douglas spruce, Colorado blue spruce, white fir, white pine, and yellow pine. Animal life is abundant, especially deer, wild turkeys, grouse, ducks, and beaver. Bears are

Fig. 45.—Inside Brazos Canyon. The trees are chiefly spruce and fir. Photograph by Standley.

said to be common, but in the autumn they were still feeding at the higher levels and no signs of any were seen.

About 800 specimens of plants were collected, special attention being given to the cryptogams, of which practically nothing is known in New Mexico. Several species of rusts were collected

which are new to the State. The lichens have been named by Mr. G. K. Merrill. Nearly all of them are additions to the known flora of New Mexico, and two of them are undescribed species. The

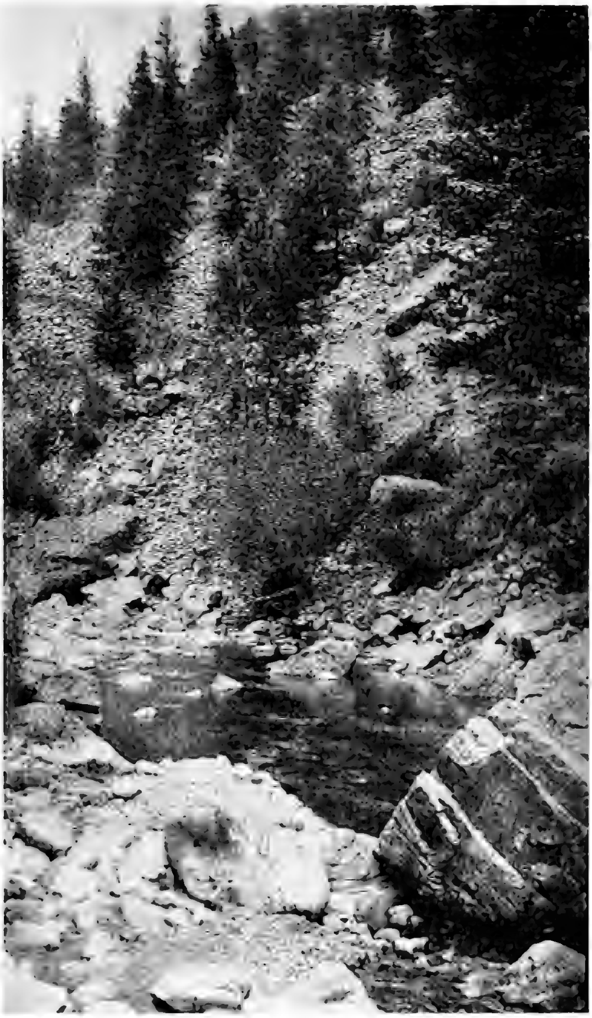

FIG. 46.—Rock slide along the Rio Brazos. Photograph by Standley.

ferns of the Brazos Canyon region are particularly interesting. Twelve species were collected, three of which were not known before from the State. The season was too far advanced to find the flower-

ing plants in the best condition—snow fell on the surrounding mountains the middle of September, just before camp was broken; but a considerable collection was obtained, nevertheless. Although only a part of the phanerogams have been determined, it is found that several species have been added to the known flora of New Mexico. Chief among the additions was a family new to the State, the Sparganiceae. Several of the plants apparently represent species new to science, descriptions of which will be published later.

FIG. 47.—Along the Rio Brazos below the canyon. Photograph by Standley.

COLLECTING FOSSILS ON CHESAPEAKE BAY

During 1914, several trips were made by Mr. William Palmer to the Chesapeake Miocene on Chesapeake Bay and some very important material was collected. Many years ago four very peculiar caudal vertebræ were described by Prof. Cope as *Cetophis heteroclitus* and these have ever since remained unique. About a dozen vertebræ of this animal were collected during the year by Mr. Palmer, and while the material is insufficient to reconstruct a skeleton, it surely indicates that a snake-like mammal of perhaps 10 feet in length and unlike anything known to-day, inhabited the Miocene sea. The skull is not known.

Material representing Zeuglodont and Squalodont mammals was also collected, indicating that representatives of those groups lived

through the greater part of the existence of the Miocene sea. One specimen is a very perfect skull evidently unlike anything heretofore known from North America. Unfortunately it contained no teeth, but teeth presumably belonging to the species were also collected. Many other vertebræ were found representing known species as well as others apparently new.

ANTHROPOLOGICAL INVESTIGATIONS IN GUATEMALA

Early in January, 1914, arrangements were made whereby Mr. Neil M. Judd of the National Museum was enabled to accept an

FIG. 48.—A view among the ruins of Utatlan, the last capital of the Quiché empire.

invitation to participate in the third season's archeological investigations at Quirigua, Guatemala, conducted under the direction of Dr. Edgar L. Hewett by the School of American Archæology. Accounts of the earlier investigations have been published by the Archæological Institute of America.[1]

Plans for the expedition of 1914 included a continuation of former excavations upon the prehistoric temples and pyramids surrounding the so-called "Temple Court," the religious center of the sacred city of Quirigua, and the reproduction, in plaster, of several of the huge stone monuments which have made these ruins world-famous. Mr.

[1] Bulletins: Vol. 2, pp. 117-134 (1911), and Vol. 3, pp. 163-171 (1912).

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FIG. 49.—Quiché Indians at Sunday morning market in the central plaza, San Tomas de Chichicastenango. Every article of native industry and art is offered for sale on market day.

FIG. 50.—A nearer view of a Quiché fire-altar near San Tomas de Chichicastenango. A horizontal stone bearing the figure of a human being and several lesser carvings stand at the back of the fire pit; rows of the young tips of spruce bows are spread in front.

FIG. 51.—Quiché Indians at fire worship, San Tomas de Chichicastenango. The worshipper stands or squats in front of the fire and mutters his prayers into the rising smoke of his burning copal cakes.

FIG. 52.—1914 excavations on the temple at the north side of the Temple Court, Quirigua, Guatemala.

FIG. 53.—Building the plaster forms around one of the Quirigua monuments. By means of these forms glue molds of the carvings were secured and, from the glue molds, plaster duplicates of the originals were constructed.

Judd was directed to superintend this latter phase of the expedition's activities, and, with the aid of a small corps of able assistants, completed casts from six of the colossal stelæ before the brief " dry season " came to an end. The task of reproduction was greatly facilitated by the use of glue or gelatine, a medium never before employed in the torrid zone. With this material, negative impressions of the carvings and inscriptions were obtained from the monuments; from these impressions, plaster duplicates of the originals were readily constructed. The results far surpassed those which had previouly been secured with other processes. The 1914

FIG. 54.—Plaster cast of a " Death's Head " from one of the Quirigua stelæ.

reports of the School of American Archæology consider, in detail, the results of its Guatemala expedition.

At the conclusion of the Quirigua work, Mr. Judd journeyed to Guatemala City and from there by Indian foot paths to the mountain valleys that lie between the capital city and the Mexican border. His object in making this trip was to gain, in the few days at his disposal, a hasty view of present anthropological possibilities among the several Indian tribes who inhabit the region. Although each village has its distinctive ethnological features, but little remains, in the remnants of the Quiché, Cachiquel, and Tzutuhil tribes, to indicate the strength and magnificence of the Quiché empire which Pedro de Alvarado destroyed in 1523, at the beginning of his conquest of Guatemala.

Among other important Indian communities, Mr. Judd visited Totonicipan and Quezaltenango (Xelahuh), former Quiché strongholds which have since become, respectively, a modernized Indian town and Guatemala's second city. One day was spent at Lake Atitlan, that beautiful body of water which played such an important part in the pre-Columbian history of the native peoples who knew its shores. Overlooking the blue lake and well-guarded from strangers, are several small villages, their gardens terracing the volcano slopes to a point beyond the drifting clouds. San Tomas de Chichicastenango, with its 16,000 Quiché Indians, and Santa Cruz del Quiché were also visited. At the former pueblo, photographs were taken of a Quiché fire-altar, with Indians at worship. Other fire-altars were noticed before the doors of the two Catholic churches whose white walls tower above the Indian houses.

Near Santa Cruz del Quiché lie the crumbling ruins of Utatlan, the last capital of the Quiché kingdom and the largest and most important of the old cities. Every block of dressed stone has been removed from the old walls and employed in the construction of the modern village—acres of massed cobblestones, plaster-paved courts, and fortifications are all that remain of Utatlan's ancient splendor. At the modern town of Santa Cruz there was an opportunity of witnessing a native play in which was depicted the reception of the Conquerors by the emperor, Nima-Quiché, and the subsequent faithlessness of the Spaniards.

Although the natives of these interior valleys have always been considered treacherous, Mr. Judd experienced few difficulties and his hurried journey seems to indicate that extended anthropological investigations in this region will be as easy as they are desirable.

ANTHROPOLOGICAL RESEARCHES IN AFRICA AND SIBERIA.

In connection with the work of the division of physical anthropology in the National Museum, two expeditions were sent out during the year 1914, under the joint auspices of the Smithsonian Institution and the Panama-California Exposition.

One of the two expeditions was in charge of Dr. V. Schück, anthropologist of Prague, Bohemia, and its objects were: 1, to study the negro child in its native environment, and thereby create a basis of comparison for the study of the negro child in our country; 2, to visit the South African Bushmen for the purpose of obtaining measurements, photographs, and facial casts of the same; and, 3, to visit British East Africa in search of the Pygmies. The tribe chosen

for the child study were the Zulu of Natal and Zululand, and over one thousand children and adolescents of all ages—ages which could be definitely determined—were examined. These data are expected to contribute some very important results to anthropology. The Bushmen were reached in the Kalahari Desert and, besides other results, 20 first-class facial casts were obtained of the people, which have since then been installed among the anthropological exhibits at San Diego. As to British East Africa, the work soon after a successful beginning was interrupted by the war; Dr. Schück was arrested and obliged to leave.

The second expedition of 1914 was in charge of Dr. St. Poniatowski, head of the Ethnological Laboratory at Warsaw. The object of this expedition was to visit a number of the remnants of native tribes in Eastern Siberia, among which are found physical types which so closely resemble the American Indian. The expedition reached two such tribes, and secured valuable data, photographs, etc., when it was also interrupted by the war.

PREPARATION OF EXHIBITS ILLUSTRATING THE NATURAL HISTORY OF MAN

Some of the results of exploration and field work by the Institution among various races of mankind are shown in connection with the anthropological exhibits of the Panama-California Exposition at San Diego. These exhibits were in preparation for over three years. They are original and much more comprehensive than any previous exhibits in this line, either here or abroad.

The exhibits fill five large connecting rooms, which occupy the building of the Science of Man at the Exposition. Four of these rooms are devoted to the natural history of man, while the fifth is fitted up as a modern anthropological laboratory, library, and lecture-room. Of the four rooms of exhibits proper, the first is devoted to man's phylogeny, or evolution; the second, to his ontogeny, or life cycle at the present time; the third, to his variation (sexual, individual, racial); and the fourth to his pathology and death.

The exhibits in room 1, on human evolution, consist of: (a) a large series of accurate, first-class casts of all the more important skeletal remains of authentic antiquity; (b) photographic enlargements and water color sketches showing the localities where the specimens were discovered; (c) charts showing the relation of the archeological position of the various finds, and their relation to the extinct fauna and to archeological epochs; (d) a series of sketches by various scientific men showing their conception of the early man,

with several illustrations of drawings, statuettes, and bas-reliefs, showing early man as drawn or sculptured by the ancient man himself; and (e) a remarkable series of ten large busts, prepared by the eminent Belgian sculptor, M. Mascré, under the direction of Prof. Rutot, representing early man at different periods of his physical advancement.

The main part of the exhibits in room No. 2, devoted to man's development at the present time, from the ovum onward, are three

FIG. 55.—Five of the Mascré-Rutot busts in the anthropological exhibits at San Diego.

series of true-to-nature busts, showing by definite age-stages, from birth onward and in both sexes, the three principal races of this country, namely, the "thoroughbred" white American (for at least three generations in this continent on each parental side), the Indian, and the full-blood American negro. These series, which required two and one-half years of strenuous preparation, form a unique exhibit, for nothing of similar nature has ever been attempted in this or any other country. Each set consists of 30 busts, 15 males and 15 females, and proceeds from infants at or within a few days after birth, to the oldest persons that could be found. The oldest negro woman is 114. After the new born, the stages are 9 months, 3 years,

Fig. 56.—A part of the Indian female series at the San Diego anthropological exhibits showing development.

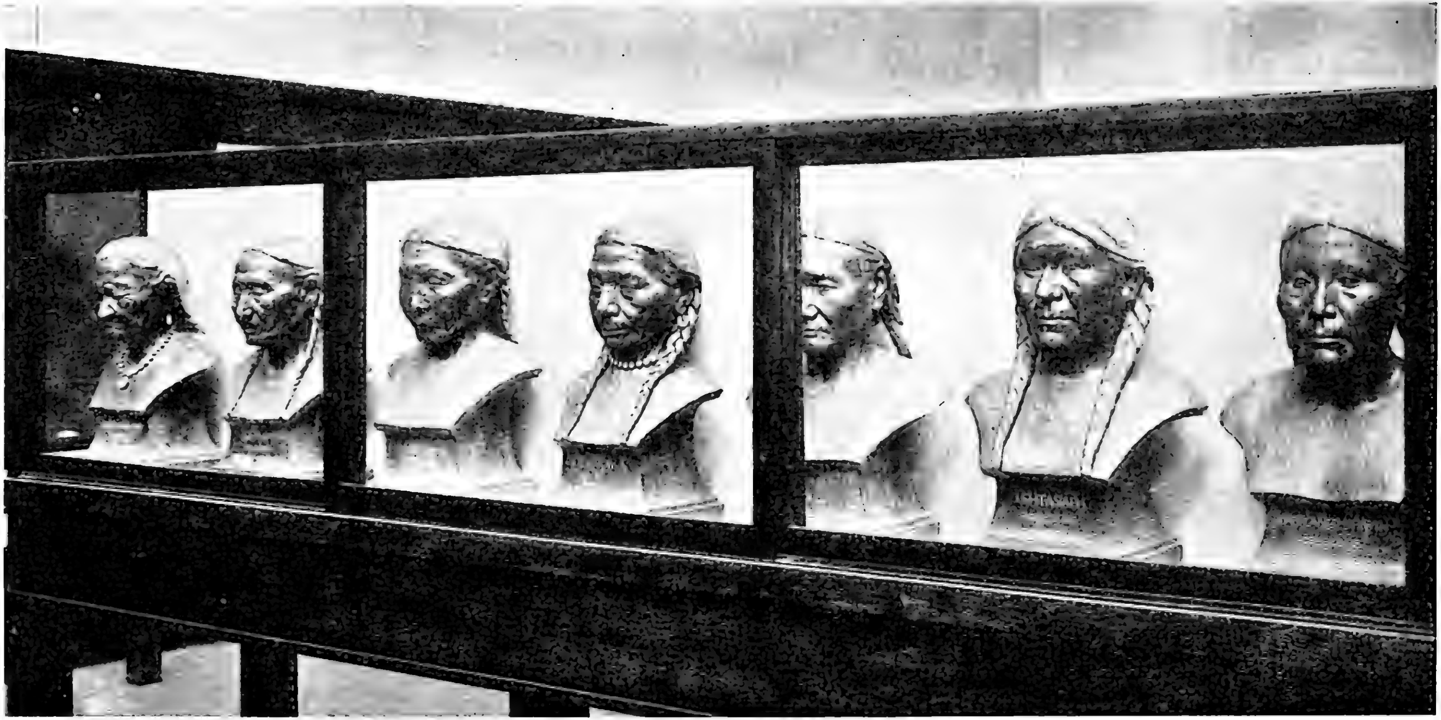


Fig. 57.—The second part of the Indian female series, showing advance with age among adults.

6, 10, 15, 20, 28, 35, 45, 55, 65 and 75 years. The utmost care was exercised in ascertaining the age, particularly among the negro and Indian. No choice was made of the subjects beyond that due to the requirements of pedigree, age, and good health. The whites and negroes were obtained, with a few exceptions, in Washington and vicinity, but their places of birth range over a large part of the Eastern, Southern, and Middle States; for the Indian, we chose the Sioux, a large, characteristic, and in a very large measure still pure-blood tribe, and one in which the determination of the ages of the subjects was feasible. Special trips were made to these people, and no pains were spared to get just what was wanted; in the case of the new born, it was actually necessary to wait until they came.

Other exhibits in room 2 show the development, by various stages, of the human brain, the skull, and various other parts of the body. A large series of original specimens show the animal forms most closely related to man at the present time, particularly the anthropoid apes; a series of charts on the walls deal with the phenomena of senility; finally, ten photographic enlargements show living centenarians of various races.

Human variation is shown in room 3 by ten sets of large busts representing ten of the more important races of man; by 200 original transparencies giving racial portraits; by over 100 bronzed facial casts, showing individual variations within some of the more important branches of humanity; and by numerous charts and other exhibits.

In room 4, a series of charts and maps relates to the death rate in various countries; to the principal causes of death in the different parts of the world, and to the distribution of the more common diseases over the earth. Actual pathology is illustrated extensively by pre-historic American material. Many hundreds of original specimens, derived principally from the pre-Columbian cemeteries of Peru, show an extensive range of injuries and diseases, such as have left their marks on the bones. In many instances the injuries are very interesting, both from their extent and the extraordinary powers of recuperation shown in the healing; while among the diseases shown on the bones there are some that find no or but little parallel among the white man or even the Indian of to-day. In addition, this room contains a series of 60 skulls with pre-Columbian operations (trepanation).

The exhibits as a whole are supplemented by a descriptive catalogue and other literature, and by frequent lectures and demonstra-

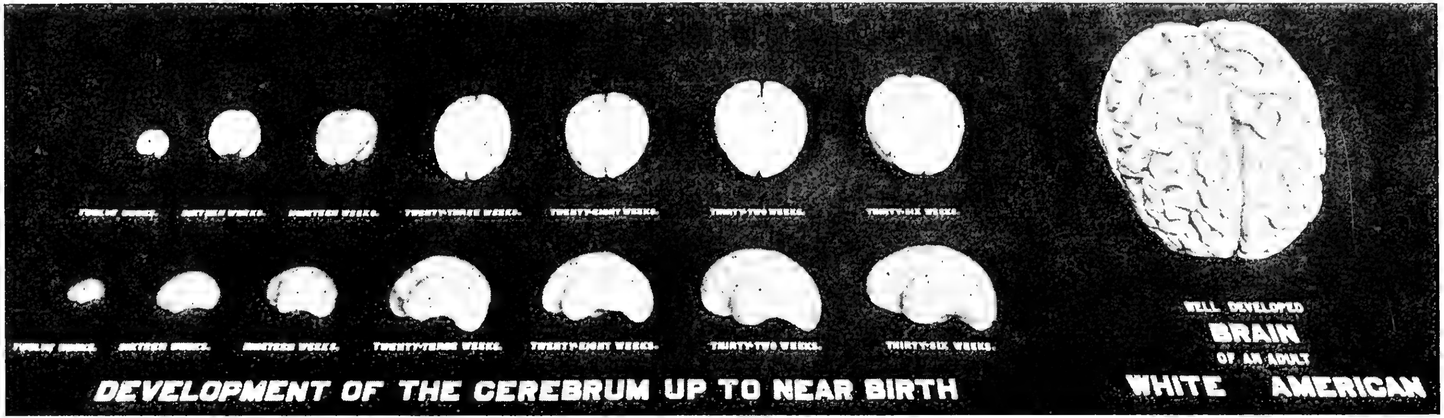


Fig. 58.—Casts in wax and plaster illustrating development of brain.

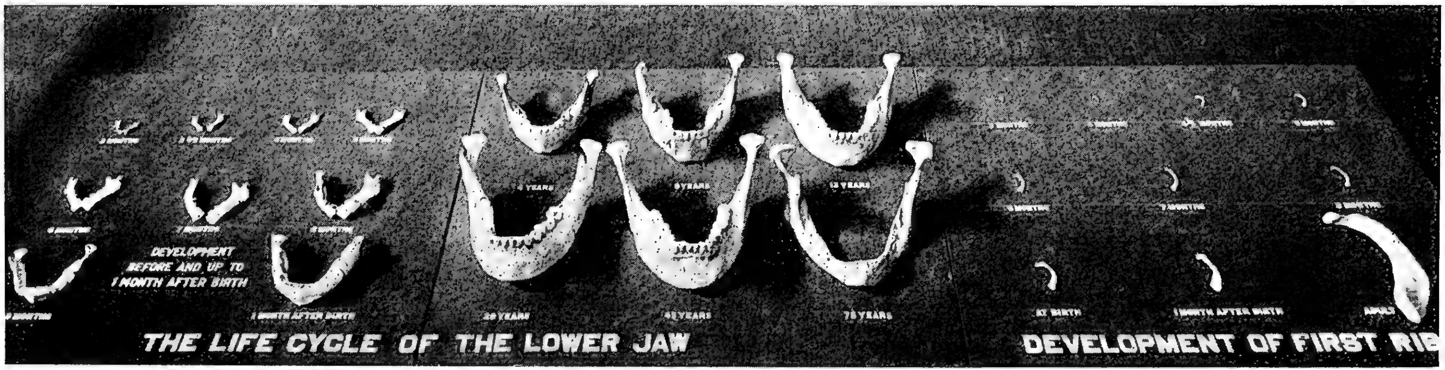


Fig. 59.—Original specimens showing pre-natal as well as later development of lower jaw and the first rib.

Fig. 60.—The development series of the American female negro, in room 2 of the anthropological exhibits at San Diego.

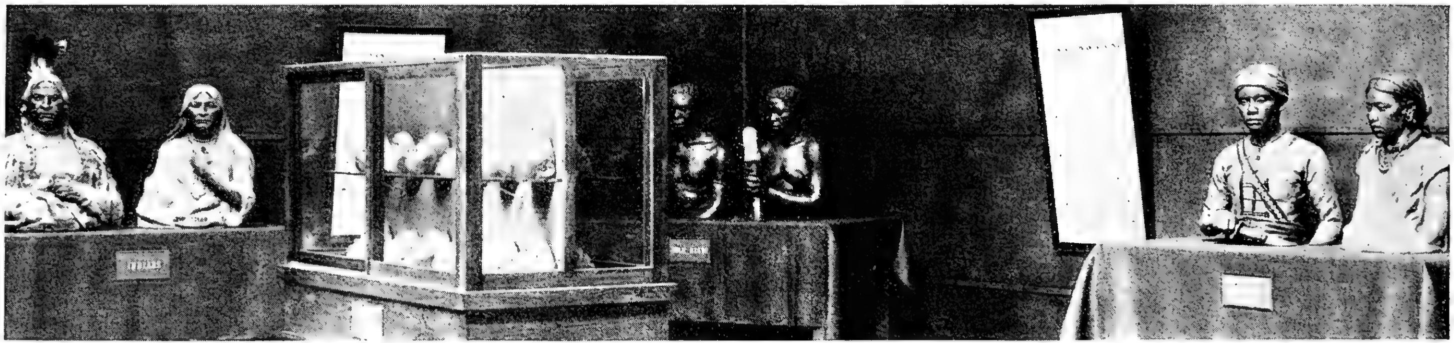


Fig. 61.—A view of a corner in room 3 of the anthropological exhibits at San Diego, showing the large racial busts, casts, and charts.

tions. They constitute an educational unit of considerable value, have attracted from the beginning the best and most serious attention, and eventually, it is hoped, will become the foundation of a museum in San Diego.

PREHISTORIC REMAINS IN NEW MEXICO

Previous to the month of May, 1914, it was pretty generally believed by archeologists that the elevated plateau extending from Deming, New Mexico, to the Mexican border was destitute of any ruins indicating a prehistoric occupation by man. In April of that year Mr. E. D. Osborn wrote to the Bureau of American

FIG. 62.—Ruin near Osborn Ranch. Photograph by J. W. Fewkes.

Ethnology that he had made a considerable collection of pottery and other objects from a village site (fig. 62) not far from his ranch, 12 miles south of that city. From the nature of these objects, especially the decoration on the pottery, photographs of a few of which accompanied his letter, it was apparent not only that the Mimbres Valley was peopled in prehistoric times by a sedentary people, but also that the former inhabitants of this valley had attained a considerable artistic development. Accordingly Dr. J. Walter Fewkes, an ethnologist on the Bureau staff, was sent to Deming to investigate these remains, and to secure, if possible, a typical collection.

He was two months in the field, confining his work more especially to the above mentioned ruin, and to the somewhat larger and more populous village (figs. 63, 64) near Oldtown, 22 miles north of the above mentioned city. He secured by excavation and purchase a

collection of over 200 objects, which are typical and regarded as an important accession to the U. S. National Museum, especially as up to that time objects illustrating the prehistoric development of the

FIG. 63.—Cliff on which Oldtown ruin is situated, overlooking Sink of Mimbres. Photograph by J. W. Fewkes.

FIG. 64.—Oldtown ruin. Photograph by J. W. Fewkes.

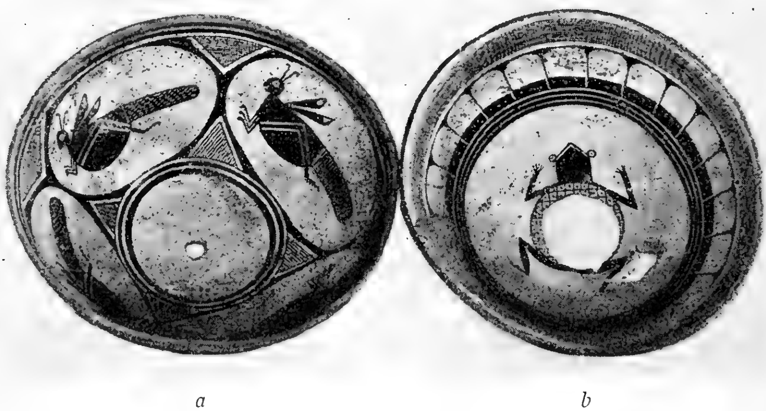
Mimbres Valley had been unrepresented in any museum in the world. A preliminary report in which these objects were described and figured was published by the Smithsonian Institution near the close of the year.[1]

[1] Smithsonian Misc. Coll., Vol. 63, No. 10 (Publ. 2316), 1914.

The majority of these specimens are mortuary food bowls, the most significant of which were decorated on their interior with painted figures representing animals known to the ancient inhabit-

a *b*

FIG. 65.—*a*, Two birds, bowl from Pictured Rocks 4 miles north of Oldtown ruin. Heye Museum. *b*, Two birds, bowl from Pictured Rocks, 4 miles north of Oldtown ruin. Heye Museum.



a *b*

FIG. 66.—Mortuary food bowls. Photographs by E. D. Osborn. *a*, Four grasshoppers, bowl from Pictured Rocks, 4 miles north of Oldtown ruin. Heye Museum. *b*, Frog, bowl from ruin at Pictured Rocks, 4 miles north of Oldtown. Heye Museum.

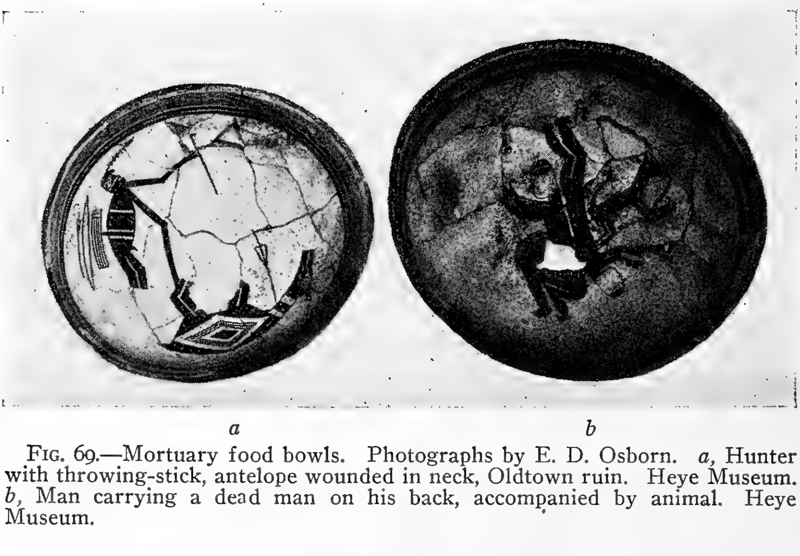
ants of the valley, and pictures of warriors or priests engaged in secular or religious observances. Some of the bowls are decorated with characteristic geometrical designs so different from any others yet found in the Southwest that it is believed that they indicate an

undescribed prehistoric culture area in the valley of the Mimbres. The symbolic and other figures show that this culture has affinities, on the one side, with ruins in Chihuahua, and on the other with the Pueblos in northern New Mexico. Some of the fragments of Mimbres pottery are identical with Casas Grandes ware.

FIG. 67.—Geometrical design. U. S. National Museum.

The elevated plateau in which the Mimbres lies is commonly known as the Sierra Madre plateau, which was a trail of migration for interchange of prehistoric cultures of Mexico and the Pueblo region. This plateau extends from the headwaters of the Gila far down into Chihuahua, including the valley of the Casas Grandes River, in which are situated the largest and best preserved ruins of northern Mexico. Between these two extremities may be traced a chain of ruins broken at a few points, indicating prehistoric connections between Mexican and Pueblo culture.

FIG. 68.—Geometrical design. U. S. National Museum.



a *b*

FIG. 69.—Mortuary food bowls. Photographs by E. D. Osborn. *a*, Hunter with throwing-stick, antelope wounded in neck, Oldtown ruin. Heye Museum. *b*, Man carrying a dead man on his back, accompanied by animal. Heye Museum.

It was found that the ancient people of the Mimbres disposed of their dead by inhumation, or earth burial, under the floors of their rooms, and that almost invariably they covered the head or face with a mortuary bowl. This bowl was artificially punctured, or "killed," before it was deposited with the dead, and in many instances the necklaces, bracelets, and other ornaments of the deceased were left on the body.

FIG. 70.—Geometrical design. U. S. National Museum.

Many of the dead were buried in a sitting posture or in the well-known contracted position; the bodies of some were extended at length or placed on one side. Evidences of cremation were not noticed, but charcoal, ashes of burnt timber, and charred corn were repeatedly found in the course of excavating. Several types of stone implements, a few of which are unique, were brought to light by the explorations made by Doctor Fewkes in the ruins of Mimbres Valley. Among the latter may be mentioned a form of rubbing stone, flat on one side but round on the opposite, in the convex surface

of which are cut grooves for the four fingers and thumb of the right hand. A large "holed stone" in the shape of a barrel, found near Oldtown, is a unique form (fig. 74) from the Southwest. One end of this is covered with shallow pits similar to those found on slabs of rocks from other ruins. The use of this stone is unknown, but, like similar holed stones from Mexico, it may have served in the ball game called *pelota*.

Fig. 71.—Geometrical design. U. S. National Museum.

A number of facts were observed in the course of these studies suggesting the probable causes of the abandonment of the prehistoric settlements south of Deming, where the majority of specimens were found. Until a few years ago, the Antelope Valley, except in its northern part or that occupied by the Mimbres, was a desert, capable of supplying water sufficient for stock but hardly adequate to meet the needs of any considerable human population. Notwithstanding this inadequacy of the water supply there is evi-

dence of the existence of several populous villages in what is now an arid desert. Evidently the region formerly had more water than at present, but the reason for its increased aridity and consequent abandonment by the prehistoric villagers was not due to a modification in climate, but to a change in the bed of the Mimbres River, which, there are reasons to believe, has occurred since the advent of man in that valley. The former course of the river past the now

FIG. 72.—Geometrical design. U. S. National Museum.

deserted villages can be easily traced, but by some shifting of the soil in its bed the river now flows to the east of the Florida Mountains. This change in direction deprived the former inhabitants of villages situated on the west side of the mountains of their supply of water, and caused them to abandon their homes.

The construction of the prehistoric buildings, as shown by an examination of the photographs of village sites (figs. 62, 63, 64), indicates that the ancient ruins in the Mimbres region had little resemblance to those of the pueblos in northern New Mexico, but

more closely resembled the fragile-walled dwellings of the Pima and Papago. The walls of the habitations were made of upright logs, chinked and plastered with clay or a natural cement (*caliche*), the base being protected by rows of stones. These walls have fallen, but the stumps of the logs, generally charred, and the rows of stones still remain, while a few feet below the surface the floor is generally

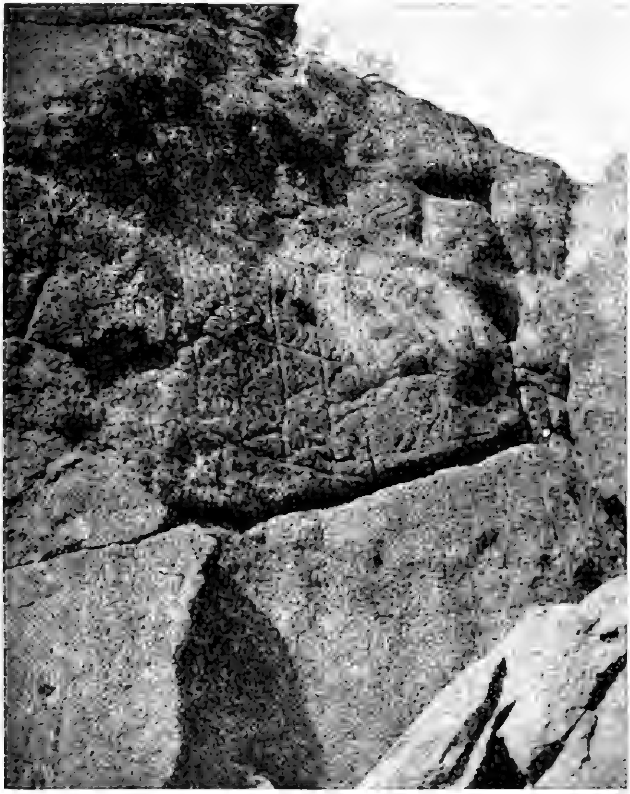


FIG. 73.—Pictographs at Pictured Rocks near Brockman's Mill. Photograph by J. W. Fewkes.

well preserved. The roof was flat and held up by one or more vertical logs in the middle of the room. The inner walls of the room were smoothly polished and apparently sometimes painted. The different families composing the population of each village were not apparently crowded into terraced communal dwellings several stories high, but lived in rancherias composed of several one-storied isolated houses.

No evidences were found in the Mimbres Valley of the former presence of walled inclosures or compounds so pronounced at Casa Grande, or of massive buildings found at Casas Grandes. Sacred rooms, or kivas, could not be distinguished from secular rooms, although clusters of depressions resembling subterranean rooms were especially abundant on the terraces along the river banks.

Fig. 74.—Pitted-holed stone, base of Oldtown Cliff. Photograph by J. W. Fewkes.

These rooms undoubtedly belonged to a very ancient type, of which the subterranean sacred room, or kiva, of the pueblo is a survival.

It is believed that the character of the prehistoric culture in the valley of the Mimbres, brought to light by these studies, is more ancient than the true pueblo of northern New Mexico, and closely related to that existing in northern Mexico in prehistoric times.

Several hot springs were examined in the upper courses of the Mimbres which were evidently once used by the natives for sacred

purposes, bones and teeth of extinct animals and stone artifacts, regarded as sacrificial offerings, having been obtained from them.

The accompanying views show the general character of designs on pottery from the Mimbres region, and sites of the ancient villages from which it was obtained.

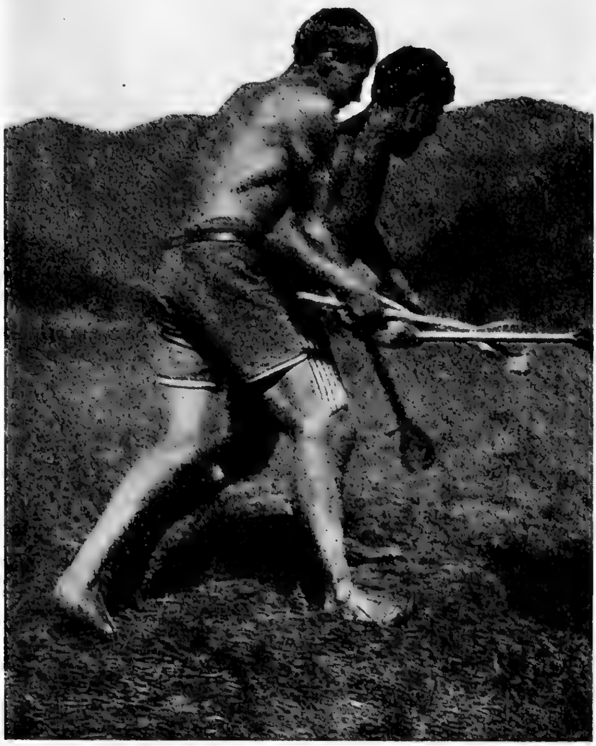


FIG. 75.—Cherokee ball play: the struggle for the ball.

FURTHER STUDY OF THE CHEROKEE SACRED FORMULAS

On June 22, Mr. James Mooney proceeded to the East Cherokee reservation in Swain and Jackson counties, western North Carolina, returning to Washington September 15. Headquarters were made with the most conservative element of the tribe, in the heart of the mountains, some 12 miles above the agency, and the time was devoted chiefly to further study and elaboration of the Cherokee Sacred Formulas previously collected. Opportunity occurred also for witnessing the ceremonial Ball Play, and by special permission of some

of the Indian priests Mr. Mooney was able to be present for the second time at the family ceremony of invoking the blessing upon the new corn and on those about to partake of it for the first time. This ceremony, probably never witnessed by any other white man, is still strictly observed in private at their homes by most of the full-blood families before tasting the new corn of the season, the priests who conduct the rite going, while yet fasting, from house to house through the settlement for that purpose. The so-called Green Corn Dance, the great tribal celebration of thanksgiving for the new corn, was last performed in 1887, on which occasion Mr. Mooney was also present. The East Cherokee, numbering now about 1,600, constitute that portion of the tribe which remained in the old home territory when the main body of the nation was removed to the West.

THE SUN AND THE ICE PEOPLE AMONG THE TEWA INDIANS OF NEW MEXICO

One of the most interesting ceremonies observed by Mrs. Matilda Coxe Stevenson during her studies among the Tewa is associated with the coming of spring or the revival of the Earth Mother from her dormant state through the winter. The Tewa are a poetic people, but they never allow their love of the beautiful to interfere with their constant efforts to sustain life. Almost every breath is a prayer, in one form or another, for food. "May we be blessed with food, more food!"—this great thought is paramount among these people who have lived in an arid country from time immemorial. Having no outside resources, everything, life itself, depends upon their own exertions and their influence with their gods. In order to gain this influence they must have priests who are capable of communing directly with the gods. "Heart speaks to heart," they say. The earth must not be wet with summer rains all the time, nor must it be perpetually covered with ice and snow: conditions must be equalized. To accomplish these desired results in past ages the Tewa were divided into the Sun and the Ice people. Each body had its rain priest as it has at the present time, the priest of the Sun people taking precedence over the priest of the Ice people. The special duty of the priest of the Sun people is to observe the rising and setting of the sun, and to bring summer rains and new creations. The priest of the Ice people observes the rising and the setting of the moon, and the moon aids him in keeping the calendars; he brings the cold rains of winter, and the snows and ice to retard plant life. The invocation says in reference to the earth: "Let our Mother sleep; let her rest so covered in ice and snow that she will sleep well

to awake with the coming of spring in all her greatness." While it is the duty of the priest of the Sun people to invoke the Sun Father to bring rains, there is a change in administration from

FIG. 76.—Juan Rey Martinez, ex-Governor and one of the most distinguished theurgists of San Ildefonso.

October 15 to February 18, when the priest of the Ice people assumes precedence over the priest of the Sun people, and he observes the rising and setting sun. He appeals to the Sun Father so to influence

Nukó^{n}se, the "black stone man of the north," and Tsä^{n} oki Kivi, the "white fog woman of the east," to send their breath to make cold the waters of the rain makers and convert them into snow and ice. Summer winds are the breath of the gods.

While the moon is feminine with many Indians, the Tewa believe the moon to be masculine and brother to the sun. In fact, these divine ones, according to Tewa philosophy, are the gods of war, born of a virgin and conceived through the embrace of the rays of the ancient Sun Father while the maiden slept on the banks of the lake Aga'chännê. Pregnant as she was, the maiden tossed in a canoe for many days upon the angry waters during the great flood that covered the earth. Finally the bark landed near the site of Santa Fe, where the maiden gave birth to twin sons. When the divine ones learned of their father they determined to find him. The earth was dark in the day and in the night, but the little fellows were guided by Kosa, star people who emitted bright light from their bodies. The father was found in a lake deep under the earth. The aged Sun Father recognized his children and wept for joy at meeting them. He said to them: "The earth is now dark, but it should have light and warmth. I will make you boys the sun and moon to pass over the earth with the burning shields of crystal." He designated the younger one to be the sun and the elder to be the moon. The divine ones were happy to remain with their Sun Father and to perform the duties assigned to them. The present sun and moon bear the names of their predecessors, Taŋsédo, "sun old man," and Po'sedo, "moon old man." They are still elder and younger brother warriors, and are appealed to as such by the elder and younger brother Bow Priests, who are the earthly representatives of these gods. The ancient Sun and Moon remain in their house below, while the divine ones do duty in the world above.

Preparatory ceremonies for the coming of spring begin at sunset of February 9th in San Ildefonso and close at sunrise the morning of the 13th. The first three nights the party disbands at midnight, provided there are no serious interruptions in rehearsing the ancient songs. This must be learned from the director of the Squash fraternity, who knows the ancient prayers and songs by heart. The first three nights the party in the kiva consists of the rain priest of the Sun people, his four male and two female associates, younger brother Bow priest, and the director of the Po''kuni, native Squash fraternity. The Bow Priest is present as guardian of its altar, and the director of the fraternity as the sage of San Ildefonso. The e'he altar is erected by the rain priest of the Sun people. On completion of the

altar the rain priest makes a sand painting on the floor a little to the northeast of the altar. First a circular ground of sand from the river bank is laid; this is outlined with a circle of black earth from the river bed; the entire disk is then covered with fine white earth; a small blue disk is next made in the center of the large one, which is then surrounded by a circle of yellow and one of red. Four crosses representing the Pleiades, are made in black upon the smaller disk. This sand painting is made in honor of the ancient Sun and Moon and remains until the close of the fourth night, when the Priests of the Bow gather the sand into a cloth and deposit it in the Rio Grande to be carried to the house of the ancient Sun and Moon.

On the fourth and last night the party in the kiva is joined by the rain priest of the Ice people, his four male and two female associates, and the elder brother Bow Priest. The priest of the Ice people sits at the northern side of the altar, the priest of the Sun people at the southern side, while the director of the Po″kuni fraternity takes his place at the north. The associates of the rain priest of the Sun people sit back of him and south of the altar, and the associates of the priest of the Ice people sit back of him and north of the altar. The two rain priests discuss the change of the seasons, the rain priest of the Sun people urging that in case the rain priest of the Ice people is not sure of his functions, he consult the priest of the Ice people of Tesuque. The rain priest of the Sun people and the director of the Po″kuni, or native Squash fraternity, make no claim to understanding the songs and prayers for ice and snow, but the sage has a perfectly clear knowledge of all ceremonies associated with the Sun people, and there is no time in the year when so important a ceremony for the good of all the people is performed as the one here described. Unless the long and most ancient rites to the "old" Sun are observed at this time, there can be no certainty of the fructification of the earth. The hearts of all the people are filled with a great desire so to please the ancient Sun Father that he will use his power to have the rain-makers send the spring rains and cause the Earth Mother to send forth her being in all its beauty.

The great ceremony is performed on the night of the 17th of February. This is no ordinary occasion. All the fraternities gather in the kiva presided over by the priest of the Sun people. Every man, woman, and child presents offerings to the ancient Sun Father, which are deposited in a heap before the altar. Each member of the order of Mystery Medicine carries the wowayí (a perfect ear of corn decorated with macaw and other plumes), and places it before

the altar. The fraternities of the Sun people take seats south of the altar, the women sitting together back of the male members. The fraternities of the Ice people sit north of the altar, the women grouping slightly apart from the men. After all the rehearsals of the priest of the Sun people and the sage of the kiva the people feel pretty sure that their songs and prayers will be recognized and received by the ancient Sun Father. All the men present sing to the accompaniment of the rattle and pottery drum. They are perhaps more profoundly interested in this ceremony than in any other, for this ritual enters into the very heart of their lives. This great ancient Sun God sits in state in his house in the lake, and it is only once a year that the people as a body invoke him. The larger the family the greater the offerings, which consist of all food that can be obtained by the Indians of to-day, and calico, cotton cloth, and a variety of other things. These offerings are made to Taŋsédo with prayers that he will see that the people may be able to secure the desired objects. All parties dance, except the priest of the Sun people and the director of the squash fraternity. These two must listen attentively that no mistake may be made in the song. The priest of the Ice people and his associates are present, having the same position they occupied at the previous meeting. He and his associates join in the dance for the new creation. The men are nude except for the breech-cloth, and their bodies are daubed in white. The women wear the native black woven dress and red belt, but arms, neck, and legs are bare. Each man carries a rattle in the right hand and a sprig of spruce in the left. The women carry an eagle-wing plume in each hand. The spruce signifies the male element, rain. The eagle plumes signify the same, for eagles live among the clouds. All night the dance and song continue, invoking the ancient one. Referring to the great heap of offerings, they sing: "We give these offerings to you; you are great, the ancient one, you who have lived always, that you will be happy and contented; that you will see that all the world receives much water that all crops may develop for good. We pray that you will talk to the rain-makers, urge them to go out and play their games and be happy, and to send rains to every quarter of the world, such rains as will uproot trees, wash out canyons, and cover the Earth Mother in water. Let her heart be great in water. And we pray that you will lift the Earth Mother from her sleep, impregnate her with your rays, and make her fruitful to look upon. Bless the whole world with her fruitfulness." These are the invocations to be heard throughout the night, when all present put their whole souls into supplicating the Ancient One for

food to sustain life. The songs continue until the first light of day, when the great heap of offerings are carried to the river and deposited to go to the ancient Sun Father. The sands of the painting are also deposited, wrapped in a cloth, in the river.

These children of nature feel every confidence that the performance of the ritual so sacred to them will bring all that their long prayers have asked for throughout the night.

WORK AMONG THE IROQUOIS

Mr. J. N. B. Hewitt left Washington on December 11, 1914, for a short field trip among the Iroquois of Ontario, Canada, and of western New York. His first stop was at Brantford, Ontario, where, with the aid of Mr. William K. Loft, a Mohawk speaker, critical phonetic and grammatic study was made of portions of Mohawk texts relating to the Iroquois League, recorded by Mr. Hewitt in former years. Work was also done in taking down a select list of Mohawk verbs for comparative purposes. His next stop was at Middleport, Ontario, where, with the aid of Mrs. Mary Gibson, the widow of the late Chief John Arthur Gibson, Mr. Hewitt recorded a long Cayuga text relating to the origin and ritual of the Death Feast; a comparative Cayuga list of verbs was also obtained. Here, with the aid of Mr. Hardy Gibson, a Cayuga chief, Mr. Hewitt was able to clear up satisfactorily certain mooted questions concerning the ritual of the League Condoling and Installation Council.

Mr. Hewitt also obtained from Mrs. Emily Carrier a list of 50 Nanticoke words which represent all that were remembered by the informant; this short list is of unique interest, as the Nanticoke dialect of the Algonquian stock has become practically extinct. Mr. Hewitt also made about 70 photographs, chiefly of persons.

OSAGE SONGS AND RITUALS

During the year 1914, Mr. Francis La Flesche, ethnologist, secured from Wá-thu-xa-ge, a member of the Tsí-zhu Wa-shta-ge, one of the two peace gentes of the Osage tribe, the rituals and songs of the Wa-xó-be A-wa-tho^{n}, which form the first of the seven degrees of the great Osage tribal war rites. It was with much difficulty that Wá-thu-xa-ge was finally persuaded to give this information. He had three reasons for refusing to give information concerning the rites, which are now being fast forgotten, as most of the older members of the tribe have adopted a new religion to which they give nearly all their thought and attention, and the younger members who are being educated care very little, if at all, for these ancient rites.

The first reason given by Wá-thu-xa-ge for refusing to recite the rituals and to sing the songs is, that he feared to make mistakes which would expose him and his family to punishment through super-

FIG. 77.—Wá-thu-xa-ge of the Tsí-zhu Wa-shta-ge, a peacemaking gens.

natural means; second, that the man who introduced the new religion, above referred to, forbade those who took up the new faith to give any further thought to the ancient rites, which he told them were the inventions of Ts'a-to^n-ga, the Great Serpent, to lead the people

astray and to prevent them from finding the true path to God; third, he suspected the man who introduced Mr. La Flesche to him, and who also belonged to the Tsí-zhu Wa-shta-ge gens, of seeking to secure a working knowledge of the rituals and songs without going through the required ceremonies and the payment of the usual fees.

The Wa-xó-be A-wa-tho^n degree of the Tsí-zhu Wa-shta-ge gens, like those of the other gentes, is divided into two great parts. The first part is called the "Seven Songs" and the second part the "Six Songs." The titles of the songs and rituals of the various gentes are generally the same, but the music and the words differ more or less. The number of the songs also varies in the degrees of the various gentes. Wá-thu-xa-ge explained that the number of songs in the war ceremonies of his gens are fewer than those of any of the other gentes because of its position in the tribe as a peace-maker, and that the performing of the war ceremonies of his gens was more a matter of form than for the purpose of encouraging a warlike spirit.

In some of the degrees the songs and rituals of both of the two parts are used, in others only those of the first part, and still in others those of the second part. While the various degrees are used in common, in forms more or less modified, by the various gentes, it is said that the "Seven Songs" belong to the Ho$^{n\prime}$-ga dual division, whose ceremonial place is at the south side of the lodge, and the "Six Songs" belong to the Tsí-zhu dual division, who occupy the north side. There also appears to be a further division of the songs and rituals among the several gentes, thus giving the rites, as a whole, a composite character.

The degree given by Wá-thu-xa-ge, whose portrait is here shown (fig. 77), is composed of six rituals and 65 songs—49 songs for the first part and 16 for the second. There are certain preliminary ceremonies that are performed before conferring a degree which contains all of the rituals and songs, or only the first or second parts. These preliminary ceremonies have also been explained by Wá-thu-xa-ge.

For many years this old man has not had occasion to perform the ceremonies, therefore his memory of them had weakened considerably. In order to refresh his memory, for the purpose of giving this information, he attended an initiation which took place a week or so before he came to Washington, although the new religion which he had adopted discouraged his witnessing, or his taking part in, any of the ancient rites. Wá-thu-xa-ge's wife, who was an honorary member of the No$^{n\prime}$-ho$^{n\prime}$-zhi^n-ga order, assisted him materially by prompting him. Wano^n-she-zhi^n-ga, whose English name

is Frederick Lookout and who a year ago was the principal chief of the Osage, not only gave assistance with what knowledge he had of the rites, but it was through his influence and urging that the old man consented to give what he remembered of them. Had "Governor" Lookout been less urgent the chances are that the old man would never have given the information and it would probably have been lost at his death.

The words of the rituals and songs of the first part of this degree have been transcribed and type-written, and the music has been transcribed from the dictaphone, but the words of the songs and the music of the second part have yet to be transcribed.

Wá-thu-xa-ge also gave, in fragments, the Ní-ki-e degree of his gens. It was difficult for him to recall all of the songs, rituals and ceremonial forms. Of this degree he gave three rituals and eleven songs. The stanzas of these songs vary in number from one to eleven. Mrs. Lookout said that the Ní-ki-e degree of the Tsí-zhu Wa-shta-ge gens is not half as long as those of the other gentes. She had taken part a number of times in some of the ceremonial forms and thus had gained her knowledge first hand.

Aside from the two degrees of the No$^{n\prime}$-ho$^{n\prime}$-zhi^{n}-ga rites, eight songs of the new religion were secured from Wá-thu-xa-ge and "Governor" Lookout, who both take active part in the exercises of this religion.

PRESERVATION OF INDIAN MUSIC

Two field trips were made by Miss Frances Densmore during the summer of 1914. The first trip was to the Standing Rock reservation in North Dakota, the purpose of which was to revise certain portions of the manuscript on Sioux music; this was accomplished by reading the manuscript to several old men of the tribe. Additional information was secured concerning the Hunka ceremony and the Spirit-keeping ceremony, as well as on other subjects which had been studied on previous visits to the reservation. Songs were also recorded to complete certain series in the material in preparation for publication.

The second trip was to the Uinta and Ouray reservation in northeastern Utah. The Indians on this reservation are the northern Ute who formerly lived in northern Colorado and are best known by their comparatively recent expedition into South Dakota, whence they were brought back by United States troops. The nucleus of that expedition was the White River band of Ute, and one of their leaders was Red Cap, chief of the White River band, whose

photograph is shown in figure 78. As the location for her work Miss Densmore selected Whiterocks, a point 15 miles beyond the agency and 80 miles from the nearest railroad. Whiterocks is the

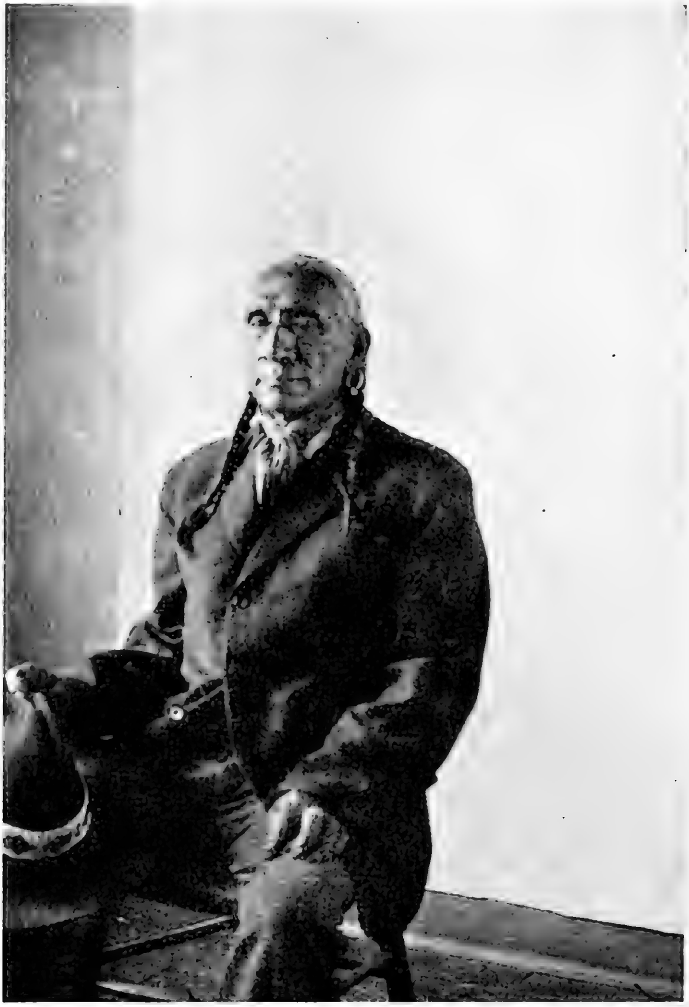


FIG. 78.—Portrait of Red Cap, chief of the White River band of Ute. Photograph by Miss Densmore.

point nearest the camps of the White River Ute, who were the principal subject of investigation.

The difficulty of the work had not been overestimated. The Indians were more conservative than any before encountered. Never having seen a cylinder phonograph, a belief gained some credence

that whoever sang into the instrument would shortly die, hence considerable open opposition developed. Fortunately, this was overcome by the exercise of patience and diplomacy.

FIG. 79.—Sub-chief of the White River band of Ute, commonly known as "Little Jim." Photograph by Miss Densmore.

FIG. 80.—Typical summer abode of the Ute on the Uinta and Ouray reservation. Photograph by Miss Densmore.

After this adjustment of relations with the Ute the work progressed with less difficulty. More than 80 songs were recorded, including songs of the Sun Dance, Bear Dance, and other native dances, as well as very old war songs, and songs used in the treat-

ment of the sick. There were also recorded several folk-stories given by a very aged woman in the manner of a chant. The songs are very diversified and show the people to be unusually musical. Among the Chippewa and the Sioux there were old men who said that when they were young the medicine-men received songs in dreams, but among the Ute this is a custom of the present time. Many "dream songs" were recorded, among them a set of six songs by a young man who said they "were taught him by a little green man who lived in a little stone house far up the mountain." Much interesting information was received concerning this mythical "green man."

The industries of these people also received consideration, and a collection of specimens representative of these industries was purchased. Among these was a bowl-shaped basket, which in old times was placed over an excavation in the ground, the singers sitting around it and accompanying their songs by the rasping together of two sticks, the longer of which was notched. This notched stick rested upon the inverted basket and the shorter was rubbed across it. This music is used only in the Bear Dance, which appears to be peculiar to these people and is still held every spring. A Sun Dance was performed last June in direct violation of orders from the Government. The Sun Dance ground was visited. Neither the Bear Dance nor the Sun Dance was held during Miss Densmore's visit, but she attended a Turkey Dance, which is the mid-summer dance of the tribe and is held about once a month.

In connection with the industries of the Ute Miss Densmore secured a fire-making apparatus in which a blunt stick and sharp sand were used, instead of the usual pointed stick. The "hearth" was similar to that in use among many tribes, except that it contained a little reservoir for the sand and a "spillway" through which the sand, heated by the friction of the rotated stick, could run down upon the fragments of bark to be ignited. A unique specimen of woven work was made for Miss Densmore, consisting of a net for fish or rabbits, formed of the outer bark of reeds, a very delicate tissue which required skilful manipulation to make it into a substantial net.

Many visits were made to the camps, figure 80 showing a typical summer abode of these Indians. Their winter homes are log huts with earth floors. At some distance from Whiterocks is the burying-ground of the Ute. The burial places are marked by the bones of horses slain at the death of their owners. An offering of corn had been placed in one of the trees, and from another hung the head of a

dog with the rope still around the neck. Tipi-poles, cooking utensils, children's toys, and clothing were among the articles placed on the graves of their owners.

The work of last summer emphasizes the close connection between the music of the Indians and the beliefs or ceremonies which they hold most sacred, and in this lies one of the advantages in the study of Indian music. If an Indian consents to sing a song he appears willing to give information which might be difficult to secure in any other manner. An instance of this is the narration of personal dreams or visions, and the relation of ceremonial duties by those who have held responsible positions in native ceremonies. The collection of Indian songs for preservation and for analysis is important, but the recording of these songs also opens the way for the securing of interesting and valuable descriptive material.

ETHNOLOGICAL RESEARCHES AMONG THE KALAPUYA INDIANS

Dr. Frachtenberg left Washington on July 6, 1914, going directly to Oregon for the purpose of concluding his investigations of the language, mythology, and culture of the Kalapuya Indians which he had commenced during the previous fiscal year. After a short trip to the Siletz and Grande Ronde agencies in northwestern Oregon, made with the object in view of interviewing all available informants, he proceeded to the United States Indian Training School situated at Chemawa, where he was soon joined, first by Grace Wheeler and, later on, by William Hartless. These two Kalapuya Indians were his chief informants, and he worked with them during the months of August, September, October, November, and part of December. This work was brought to a conclusion by a stay at the Grande Ronde agency that lasted from December 13 until December 20; this brief time was spent mainly in collecting material for a comparative study of the Kalapuya dialects. A planned trip to the Yakima reservation for the purpose of interviewing the sole survivor of the Atfalati tribe had to be abandoned, owing chiefly to the lack of funds.

Dr. Frachtenberg's field work proved highly successful. He obtained 30 myths, tales, historical narratives, and ethnographic descriptions, told in the various Kalapuya dialects, an unusually large amount of grammatical notes, sufficient material for a linguistic map of the several Kalapuya dialects, and some data on Kalapuya ethnology.

A glance at this material reveals some very interesting facts. The Kalapuya Indians in former days were the most powerful and numerous family inhabiting the present State of Oregon. They claimed possession of the whole fertile valley of the Willamette River, which extends from the Coast Range on the west to the Cascade Mountains on the east. Their settlements reached as far north as Portland and as far south as the middle course of the Umpqua River. This territory comprises an area of approximately

FIG. 81.—Charles Bradford and wife, Smith River (Athapascan) Indians. Courtesy of Dr. Max F. Clausius, Siletz, Oregon.

12,000 square miles; and its topographic nature, its rich fauna and flora, its streams that abound in all kinds of fish, justify the assumption that it sustained a large number of inhabitants. These Indians were brought into the Grande Ronde agency in 1857, at the close of the Rogue River war. Unfortunately tribal wars and epidemics of smallpox and tuberculosis have decimated the several Kalapuya tribes to such an extent that Dr. Frachtenberg found a mere handful of these natives, and the time is not far off when the Kalapuya Indians, like so many other tribes of the Northwest, will have become an extinct group.

FIG. 82.—Ed Bensell and wife, Makwana-lunne (Athapascan) Indians, dressed for a "Feather Dance."

Fig. 83.—Jennie Rooney, an aged Tula-lunne (Athapascan) woman, ready to participate in the "Feather Dance."

The Kalapuya family embraces a number of tribes, the most important of which are given here as follows: (1) Atfalati, living formerly on the banks of the Tualatin River; (2) Yamhill, claiming as their possessions the banks of the river bearing their name; (3) Lakmayuk, who derived their name from the River Luckiamute; (4) Marys River (Calapooia Proper), whose settlements were situated along the banks of the Calapooia and Marys rivers; (5) Yonkalla, the most southerly Kalapuya tribe; (6) Ahantsayuk, also called Pudding River Indians; and (7) Santiam, who formerly lived on the banks of the Santiam River.

These several tribes spoke varieties of the Kalapuya language that show remarkable lexicographic diversity. Morphological differentiation exists also, but it is chiefly of a phonetic nature. All differences between the various Kalapuya dialects seem to have been caused by a geographic distribution, resulting in three subdivisions, within which idiomatic differentiation is very slight. Thus, the Yamhill and Atfalati dialects form one subdivision; Ahantsayuk, Santiam, Marys River, and Lakmayuk form the second, while Yonkalla belongs to a group of its own.

The Kalapuya language, while showing great phonetic variations (such as the occurrence of a labial spirant *f* and the presence of the trilled *r*), is structurally closely related to the languages of the neighboring tribes, such as the Coos, Siuslaw, Yakonan, Salish, and Athapascan. It belongs to the same type; that is to say, similar psychologic concepts are expressed by means of identical grammatical processes. The language belongs to the suffixing type. Its mythology differs in no way from the mythologies of the other tribes of western Oregon, being characterized by the absence of a distinct creation myth and by the preponderance of animal tales belonging chiefly to the Coyote cycle. An interesting phase of Kalapuya mythology is the presence of elements of European folk-lore, especially the absorption of French fairy tales that deal with the exploits of the orphan Petit Jean. This feature will be made the subject of a separate paper, which will probably appear in the near future.

The long and continued contact of the Kalapuya Indians with white settlers has resulted in a complete breaking down of their native culture and mode of living. Consequently, the ethnological data that could be obtained by Dr. Frachtenberg were very meager and, in most cases, were given as information obtained through hearsay.

INVESTIGATIONS AMONG THE STOCKBRIDGE, BROTHERTON, AND FOX INDIANS

Early in July Dr. Michelson left for the United States Indian School at Carlisle to arrange for future translations of his Fox texts by Horace Poweshiek, as well as to obtain some linguistic notes on Sauk and Fox. He then proceeded to Wisconsin to investigate the Stockbridge Indians. His headquarters were at Keshena. About

FIG. 84.—Fox sacred pack.

a dozen persons were found who could give isolated words in the Stockbridge (Mahican) language, but only one person who could dictate connected texts. About a half dozen of such texts were obtained with difficulty. Knowledge of the language was too far gone to permit unraveling its details, but nevertheless sufficient material was obtained to show conclusively that Stockbridge belongs closely to Natick and Pequot-Mohegan, which are closer to each other than either is to Stockbridge. Stockbridge likewise shows certain affinities with Delaware-Munsee. If more material can be obtained on a future visit, a brief memoir on this language may be expected.

FIG. 85.—Fox sacred pack.

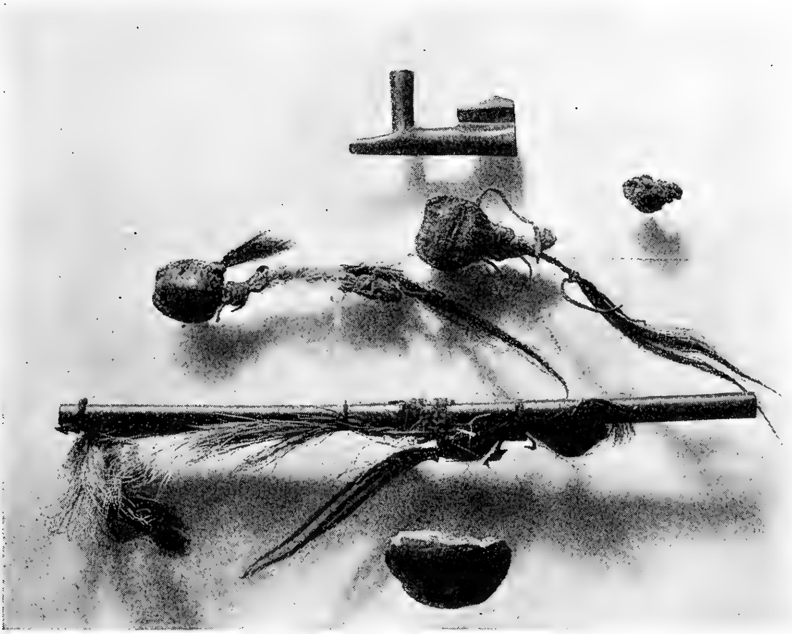


FIG. 86.—Contents of Fox sacred pack.

Some incidental notes on Menominee linguistics and ethnology were obtained.

Among the Stockbridge, near Lake Winnebago, only one person was found who could give even isolated Stockbridge words, and no one who could dictate texts.

FIG. 87.—Contents of Fox sacred pack.

There are probably no absolutely pure-blood Stockbridge Indians living, though perhaps 50 are nearly so; the remainder show various degrees of mixture with white and negro blood, and some with both; however, in all cases the Indian characteristics predominate.

Dr. Michelson next proceeded to investigate the so-called Brotherton Indians near Lake Winnebago. Unfortunately not a single

person had knowledge of anything Indian except the tribal history. Here again no full-bloods could be found; practically all showed a large infusion of white blood.

FIG. 88.—Alfred Kiyama, full-blood Fox Indian, age 45. Tama, Iowa.

He next went to continue his work among the Foxes of Iowa. Here particular attention was paid to ritualistic origins; likewise some translations of myths and tales were obtained. Some information was also procured concerning the ancient Midewiwin ceremonies. This information, however, must be checked by the Sauk

of Kansas and Oklahoma, as these ceremonies are now extinct among the Foxes proper.

The accompanying photographs are those of a Fox sacred bundle, with its contents, which is now in Berlin, and of a Fox Indian.

STUDIES OF SOLAR RADIATION

Mount Wilson work.—The Astrophysical Observatory continued its observations on Mt. Wilson, Cal., for the purpose of measuring the intensity of the sun's radiation, as it is at the surface of the earth,

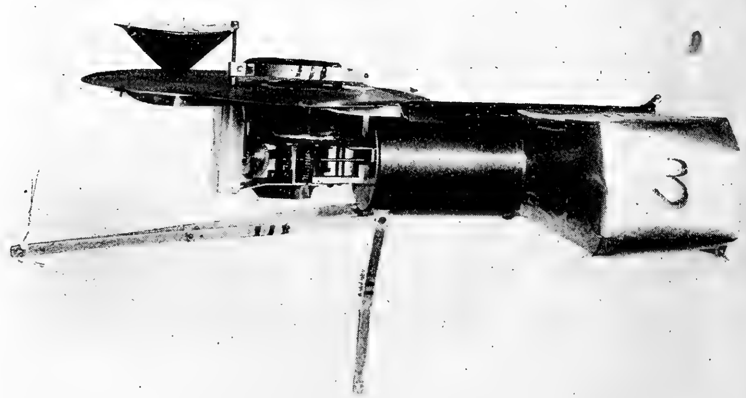


Fig. 89.—Balloon Pyrheliometer.

and the losses which it sustains in passing through the atmosphere, so as to permit the determination of the mean intensity outside the atmosphere, which is called the solar constant of radiation. As shown in former years, solar radiation is really not strictly constant, but is variable. The observations were made at Mt. Wilson on every favorable day throughout the period of the stay of the expedition, from May until November, in order to study the progress of this variability of the sun.

In connection with this work, the observatory was equipped with a tower telescope of 75 feet focus in the autumn of the year 1913. This instrument has been employed for the study of the distribution of light over the image of the sun, and the results indicate that this

distribution is variable from day to day. This variability appears to be closely correlated with the variation of the total radiation of the sun revealed by the solar constant investigations. It is confidently hoped that further study of these two interesting phenomena will throw light on the nature of the sun's radiating envelope.

Sounding balloon work at Omaha.—In order to more thoroughly confirm our determinations of the solar constant of radiation, measurements were undertaken in connection with the U. S. Weather Bureau at Omaha. Sounding balloons were sent up early in July, 1914, equipped with recording pyrheliometers (fig. 89). The work was in the charge of Mr. L. B. Aldrich, on the part of the Smithsonian Institution, and of Dr. William R. Blair, on the part of the Weather Bureau. Three instruments were sent up and all were recovered. One of these was sent by night as a check on the accuracy of the work, and the other two by day, with the hope of measuring the intensity of the sun's radiation at enormous altitudes. The pyrheliometer was suspended by means of wire 22 meters below three balloons each 1.25 meters in diameter, weighing with the apparatus about 23 pounds. An altitude of 15 miles was reached on July 11 when, as expected, two of the balloons burst by expansion and the third balloon brought the pyrheliometer down in safety near Carson, Iowa.

One of the instruments made a very fine record of solar radiation and fortunately was recovered entirely uninjured, and it has been repeatedly tested and standardized at Washington. The tests are not yet completely finished, but they indicate that three excellent determinations of the solar radiation were made at heights so great that the pressure of the air was extremely small, certainly much less than one-twentieth of that which prevails at sea-level. The results, when reduced to mean solar distance and corrected for all known sources of error, come between 1.8 and 1.9 calories per sq. cm. per minute, with a probable error of about 3 per cent. This result is in close accord with the values of the solar constant of radiation secured by spectrobolometric measurements in former years on Mt. Wilson, Mt. Whitney, Bassour, Algeria, and at Washington.

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TWO NEW SEDGES FROM THE SOUTH-WESTERN UNITED STATES

BY

KENNETH K. MACKENZIE

(Publication 2364)

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TWO NEW SEDGES FROM THE SOUTHWESTERN UNITED STATES

By KENNETH K. MACKENZIE

In going over the collections of the Agricultural College of New Mexico, two species of Carex, which are apparently undescribed, have been noted. At the request of Mr. Paul C. Standley, who wishes to use the names in the Flora of New Mexico, soon to be published, descriptions are given herewith.

CAREX WOOTONI Mackenzie, sp. nov.

Clumps medium-sized, without long running rootstocks, the culms 3-6 dm. high, usually exceeding the leaves, slightly roughened on the angles above, phyllopodic; leaves with well developed blades, 3-8 to a culm, on the lower third, the sheaths overlapping, white-hyaline opposite the blades, the blades flat, 1.5-3.5 mm. wide, 1-2 dm. long, roughened toward the apex; blades of sterile culm leaves longer and more attenuate; inflorescence consisting of 3-8 spikes aggregated into a head 1.5-4 cm. long and 1-2 cm. wide, the spikes ovoid-oblong, 8-16 mm. long, 6-8 mm. wide, containing a few inconspicuous staminate flowers at base and numerous appressed-ascending perigynia above; lowest bract 3 cm. long or less, 2-4 mm. wide at base, usually long-cuspidate, with hyaline margins at base and often brownish tinged; upper bracts much shorter or wanting; scales ovate, brownish, with green midrib and hyaline margins, usually acute but varying from short-cuspidate to acutish, narrower and noticeably shorter than the mature perigynia; perigynia lanceolate or narrowly ovate-lanceolate, 7 mm. long, 2.5-3 mm. wide, narrowly winged to the base, the margins often incurved, nerveless or nearly so on both faces, noticeably dilated by the thick achene, round-tapering at base, tapering at apex into the serrulate, shallowly bidentulate beak, this about one-fourth the length of the whole perigynium and winged to near the tip; achenes lenticular, with oblong faces, 2.5 mm. long, 1.5 mm. wide, rounded to a nearly sessile base, rounded at apex, tipped by the straight style; stigmas two.

This plant of the mountains of New Mexico and Arizona has heretofore been referred to the northern *Carex petasata* Dewey (*Carex Liddonii* Boott). In the size and shape of its perigynia the resemblance is very strong, but that species has perigynia strongly and finely nerved on both faces, and in addition its scales are equal in length to the perigynia, while in the species here proposed the perigynia are nerveless or nearly so and the scales are noticeably shorter than the perigynia. The long narrow perigynia with margins serrulate to the tip serve to distinguish it from *Carex festiva* and its allied species.

Specimens examined—New Mexico: San Francisco Mountains, *Wooton,* July 15, 1892 (type, in herb. New Mexico Agricultural College); Winter Folly, Sacramento Mountains, Otero County, *Wooton,* August 13, 1899; North Eagle Creek, White Mountains, Lincoln County, *Turner 204,* September 14, 1899. Arizona: Southern slope of San Francisco Mountains, *Cannon and Lloyd,* August, 1904.

CAREX RUSBYI Mackenzie, sp. nov.

Culms strictly erect, densely cespitose, 2.5-3.5 dm. high, much exceeding the leaves, roughened on the angles above, brown and slightly fibrillose at the base; leaves with well developed blades, usually three or four to a culm, clustered near the base, the blades erect-ascending, flat, with somewhat revolute margins, 1.5-3 mm. wide, 1-2 dm. long, roughened on margins, the sheaths tight, not readily breaking, not septate-nodulose, the opaque part neither transversely rugulose nor red-dotted; spikes about five, all aggregated into a rather stiff head, this 1.5-2.5 cm. long and about 7.5 mm. wide, the upper spikes scarcely distinguishable, the lower readily distinguishable but little separated, each spike bearing the rather inconspicuous staminate flowers above and the one to five ascending perigynia below; bracts (except lowest) inconspicuous and resembling the scales, the lowest bract exceeding its spike, 1 cm. long, enlarged at base and terminating in a long cusp; scales ovate, white-hyaline, with green midrib, faintly tinged with reddish brown, acuminate or cuspidate, about the width of and rather shorter than the perigynia, these not completely concealed; perigynia narrowly ovate, strongly plano-convex, with slightly raised borders, somewhat spongy at base, nerveless or nearly so, 4 mm. long, about 1.75 mm. wide, tapering to the substipitate base, tapering to the minutely serrulate or nearly smooth beak, this about one-third the length of

the body, minutely hyaline-tipped, obliquely cut or in age very shallowly bidentate; achenes lenticular, with short oblong face, 2.75 mm. long, 1.5 mm. wide; style slender, straight, not enlarged at base; stigmas two.

Among the specimens cited by me in describing *Carex neomexicana*[1] are two specimens collected in Arizona by Dr. H. H. Rusby. Further study of these specimens has convinced me that while they have a strong resemblance to that species they represent an entirely distinct plant. In *Carex neomexicana* the perigynium beak is deeply bidentate and strongly serrulate, and the rootstock is short-creeping. In Dr. Rusby's specimens the perigynium beak is obliquely cut, or in age very shallowly bidentate, and minutely serrulate or nearly smooth on the margins, while the culms are densely cespitose. The northern species described by me as *Carex brevisquama*[2] is closely related but is distinguished by its smaller perigynia, less cespitose culms, and more strongly reddish brown tinged scales.

In addition to Dr. Rusby's specimens collected in 1883 in Yavapai County, Arizona, nos. 859 (type, herb. N. Y. Bot. Gard.) and 855, Mr. E. O. Wooton has collected the same species at Van Patten's Camp, in the Organ Mountains, Dona Ana County, New Mexico (May 14, 1899).

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[1] Bull. Torrey Club **34**: 154. 1907.

[2] An earlier name for this northern plant is *Carex vallicola* Dewey. The type, which I have seen recently, is a young plant with little developed perigynia. In mature plants the bracts and scales are much less prominent than they appear in the type.

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REPORT UPON A COLLECTION OF FERNS FROM WESTERN SOUTH AMERICA

BY
WILLIAM R. MAXON

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REPORT UPON A COLLECTION OF FERNS FROM WESTERN SOUTH AMERICA

By WILLIAM R. MAXON

The specimens of ferns and fern allies discussed in the following pages are part of an interesting collection made in Peru, Bolivia, and Chile in the latter half of 1914 by Dr. and Mrs. J. N. Rose. They were gathered incidentally during the progress of a field investigation of the cactus flora of western South America by Doctor Rose, as Research Associate in Botany, Carnegie Institution of Washington, under the joint auspices of the Carnegie Institution and the New York Botanical Garden, this exploration being part of a larger project looking to the preparation of a monograph of the Cactaceae by Doctor Rose and Dr. N. L. Britton. It being impracticable to make large general collections, attention was given to a few groups, other than the Cactaceae, such as the ferns, grasses, and certain genera of Compositae. Of the ferns and fern allies, 25 species were collected, five of which are apparently new. These are described herein, together with a Peruvian species of Notholaena first gathered by the Wilkes Expedition and never properly distinguished under a valid name. The rather high proportion of new species is suggestive of the great amount of botanical exploration yet to be done in these interesting regions.

A duplicate set of the ferns, as well as of other herbarium material of this collection, is deposited in the herbarium of the New York Botanical Garden. The numbers are in continuation of Doctor Rose's earlier series, given mainly to Mexican plants.

POLYPODIACEAE

CAMPYLONEURUM AUGUSTIFOLIUM (Swartz) Fée

PERU: Cuzco, alt. 3,300 meters (19062). Vicinity of Oroya, alt. 3,700 meters (18691).

POLYPODIUM MOLLENDENSE Maxon, sp. nov.

Rhizome creeping, curved or subintricate, 2 to 3 cm. long, 2 mm. in diameter, coarsely radicose, densely paleaceous, the scales widely imbricate, appressed, 2.5 to 3.5 mm. long, very narrowly attenuate-

acuminate from a deltoid-ovate rounded base (here 0.7 to 1.1 mm. broad), light brown in mass, definitely but not sharply bicolorous, the darker median area composed of short to elongate, distinctly luminate cells with reddish brown sclerotic partition walls; marginal zone composed of mostly transverse, thin-walled, whitish cells in 2 to 4 rows, the outermost ones disposed as a deeply and irregularly denticulate margin, the teeth cleft. Fronds several, approximate, 4 to 8 cm. long; stipe 1.5 to 3 cm. long, light brownish, narrowly marginate along the ventral face; lamina deltoid-oblong, long-acuminate, 2.5 to 5.5 cm. long, 1 to 2.5 cm. broad, obliquely pinnatifid to within 1.5 mm. of the rachis, the rachis evident beneath, dark brown; segments 5 to 9 pairs, oblong to linear-oblong, dilatate, unequal, the upper ones gradually shorter, finally evident as short oblique lobes merging into the narrowly elongate apex; margins subentire to lightly crenate; midveins concealed; veins 4 to 6 pairs in the larger segments, wide-spreading, mostly once forked half way to the margin, the sori terminal upon the first branch, the other branch ending in a minute depressed hydathode near the margin; lower surface sparsely paleaceous, the scales resembling those of the rhizome in general structure, but much shorter (0.3 to 0.5 mm. long) and commonly elongate-deltoid, the dark cells with larger lumina, the margins more deeply lacerate-denticulate; sori 3 to 6 pairs, medial, not concealed by scales; sporangia glabrous, the annulus 14-celled; spores diplanate, pale, granulose. Leaf tissue elastico-coriaceous, the segments tortuous or irregularly involute in drying, or the whole lamina reversely circinnate.

Type in the U. S. National Herbarium, no. 700538, collected in low hills back from the coast near Mollendo, Peru, August 5, 1901, by R. S. Williams (no. 2978). Collected also at the same locality, August 25-26, 1914, by Dr. and Mrs. J. N. Rose (no. 18989).

Related closely to *P. pycnocarpum* and several allied South American species variously confused under this name. These are treated at length in a paper soon to be published in the Contributions from the U. S. National Herbarium.

POLYPODIUM PYCNOCARPUM C. Chr.

PERU: Near Oroya, alt. 3,700 meters (19467).

ADIANTUM EXCISUM Kunze

CHILE: Vicinity of Choapa, alt. 235 meters (19511).

ADIANTUM GLANDULIFERUM Link

CHILE: Near Valparaiso, near sea-level (19125). Vicinity of Choapa, alt. 235 meters (19220). Between La Ligua and Los Molles, Province of Aconcagua, alt. about 100 meters (19394).

ADIANTUM ORBIGNYANUM Mett.

PERU: Vicinity of Oroya, alt. 3,700 meters (18700).

ADIANTUM SCABRUM Kaulf.

CHILE: Vicinity of Choapa, alt. 235 meters (19512).

CHEILANTHES ORNATISSIMA Maxon, sp. nov.

Rhizome multicipital or usually single, erect, woody, bulbiform, 1 to 1.5 cm. high, 1 to 2 cm. in diameter, densely paleaceous, the scales erect, very closely tufted, fulvous to castaneous, 5 to 10 mm. long, mostly less than 0.3 mm. broad at the base, nearly capillary (the cells long and extremely narrow, attenuate, the walls nearly hyaline), slightly tortuous, with a few distant, minute, mainly antrorse teeth. Fronds numerous, cespitose, erect or ascending, mostly arcuate, 8 to 16 cm. long, very densely paleaceous; stipes 1 to 4 cm. long, 1.3 to 1.8 mm. in diameter, brown and sublustrous beneath a dense persistent covering of imbricate scales similar to those of the under side of the lamina; lamina linear to oblong-lanceolate, 6 to 14 cm. long, 1.5 to 6 cm. broad, exactly tripinnate, long-acuminate; pinnæ 15 to 20 pairs, mostly imbricate, the larger ones 3 to 4 cm. long, 7 to 12 mm. broad, oblong to linear-oblong from a slightly broader base, obtuse or acutish, sessile, spreading or upwardly falcate, the lower surface wholly obscured by a dense covering of very large, widely imbricate, brownish-centered scales, the broad, diaphanous, whitish borders irregularly denticulate-ciliate to copiously lacerate-filamentose, the tangled capillary divisions recurved, mostly extending between the segments to the upper surface of the lamina and nearly covering it; pinnules 6 to 9 pairs in the larger pinnæ, approximate, broadly oblong, pinnate, the 2 or 3 pairs of segments distant, minute, sub-globose, crenately lobed, conspicuously revolute, the minute few-sporangiate sori borne on the back of the lobes at the wholly unchanged margin; sporangia glabrous; spores triplanate, closely tuberculate.

Type in the U. S. National Herbarium, no. 515998, collected in the high mountains back of Lima, Peru, March, 1892, by William E.

Safford (no. 996). Besides additional material of the type collection there are at hand two further collections: (1) a small but complete specimen of the Wilkes Exploring Expedition, hitherto unnamed and not mentioned by Brackenridge, labelled merely "Peru," and (2) excellent small specimens collected near Oroya, Peru, altitude 3,700 meters, July 14, 1914, by Dr. and Mrs. J. N. Rose (no. 18707). All of these specimens are clearly of one species, despite the extremes of size.

Cheilanthes ornatissima is without much doubt the species illustrated by Hooker[1] as "*Cheilanthes scariosa* Presl," and probably represents the species passing under this name in herbaria. It is not, however, the Peruvian plant which Presl had in hand in describing his *Cheilanthes scariosa,* which appears to be a form of *C. myriophylla.* Presl cites as a synonym *Acrostichum scariosum* Swartz, 1806, founded on a Mexican plant first described as *Acrostichum lanuginosum* Willd., 1802 (not *A. lanuginosum* Desf., 1800); but this again is different, being reckoned a Notholaena by Christensen under the name *N. scariosa* (Swartz) Baker. Obviously, then, since the name *Cheilanthes scariosa* Presl was not originally proposed for a supposed new species, but was intended as a transfer of the older name *Acrostichum scariosum* Swartz, it is inadmissible to use it for a second species, as has been done by Christensen. But leaving out of consideration the matter of nomenclature, it will be seen from a careful reading of Presl's description that Hooker's plant is very different from Presl's. The former is almost certainly that here described as *C. ornatissima;* the latter is, in all probability, *C. myriophylla* Desv.

Cheilanthes ornatissima is the most densely and copiously paleaceous species of Cheilanthes known to the writer, the scales of the under side of the lamina being not only very large but widely overlapping and extending beyond the edges of the segments to form a thick, solid, unbroken protective covering, entirely concealing the segments. The cellular structure of the scales is very minute; the surfaces are finely lineolate, the cells being very narrow and greatly elongate, pointed, and with thin, almost colorless partition walls. This is in marked contrast to *C. Incarum,* described hereafter.

The upper surface of the lamina of *C. ornatissima* bears a lax but close covering of long, coarse, silky, white "wool," which upon careful dissection is found to proceed from the under side of the

[1] Sp. Fil. **2**: *pl. 104. A.*

lamina and to consist of the copiously filamentose extremities of the widely imbricate scales just described. Aside from this derived covering the upper surface of the segments is glabrous, no scales or hairs whatever arising from it.

CHEILANTHES INCARUM Maxon, sp. nov.

Rhizome decumbent, woody, about 2 cm. in diameter each way, very coarsely radicose beneath, densely paleaceous above, the scales flaccid but erect and closely tufted, light castaneous, 10 to 15 mm. long, 0.25 to 0.35 mm. broad, linear-ligulate, long-attenuate (the cells linear to narrowly oblong, indistinct, acutish or mostly obtuse), sharply flexuous toward the apex, here provided with numerous large, curved, elongate, mainly retrorse teeth, similar but smaller teeth borne upon the margins sparingly throughout. Fronds numerous, cespitose, erect, arcuate, 12 to 18 cm. long, densely paleaceous beneath; stipes 4 to 6 cm. long, 1 to 1.3 mm. in diameter, dull reddish brown beneath a persistent paleaceous covering like that of the lamina beneath; lamina narrowly lanceolate-elliptic, 9 to 12 cm. long, 1.8 to 2.8 cm. broad, attenuate at the apex, slightly narrowed at the base, bipinnate; pinnæ 13 to 18 pairs, sessile, the lowermost 2 or 3 pairs distant, the others adjacent but scarcely imbricate, the larger ones 1 to 1.6 cm. long, 5 to 7 mm. broad, elongate-deltoid, inequilateral, obtuse or acutish, broadly ascending, strongly involute, the lower surface wholly obscured by a dense covering of large, broadly imbricate, whitish or yellowish brown, nearly concolorous, deltoid-ovate, denticulate-ciliate scales, the acuminate tips of many of these recurved upon the upper side of the otherwise glabrous pinnæ; pinnules of the larger pinnæ 4 or 5 pairs, spreading, the larger ones pinnately divided with 1 or 2 pairs of sessile or semiadnate, roundish segments, the others crenately lobed, or the apical ones simple; segments not lobed, slightly revolute, the few-sporangiate sori terminal upon the veins at the slightly modified margin; sporangia glabrous; spores triplanate, closely tuberculate.

Type in the U. S. National Herbarium, no. 761644, collected near Cuzco, Peru, altitude 3,300 meters, September 1, 1914, by Dr. and Mrs. J. N. Rose (no. 19061).

Related to *C. ornatissima,* from which it differs in its less dissected lamina, more distant pinnæ, and less widely revolute segments, and in the character of its paleaceous covering. The scales of the under surface are deeply denticulate-ciliate but not at all filamentose, the upper side of the lamina being only partially covered by the slender

recurved apices of the dorsal scales and lacking altogether the fine silky white covering described as characteristic of *C. ornatissima.* Their structure is equally distinctive, the cells being mostly large, widely pentagonal or hexagonal, with yellowish sclerotic partition walls and large lumina, contrasting in a very pronounced way with the finely lineolate scales of *C. ornatissima.* The rhizome scales are very different also, as may be noted from the description, the divaricate-flexuose tips and strongly toothed margins of *C. Incarum* being characteristic.

CHEILANTHES MYRIOPHYLLA Desv.

PERU: Matucana, alt. 2,375 meters (19465).

CHEILANTHES PRUINATA Kaulf.

PERU: Juliaca, alt. 3,800 meters (19094).

NOTHOLAENA NIVEA (Poir.) Desv.

PERU: Vicinity of Oroya, alt. 3,700 meters (18701). Cuzco, alt. 3,300 meters (19063).

BOLIVIA: Vicinity of La Paz, alt. 3,600 meters (18917). Vicinity of Oruro, alt. 3,700 meters (18935).

NOTHOLAENA TENERA Gill.

PERU: Near Cuzco, alt. 3,300 meters (19471).

NOTHOLAENA HYPOLEUCA Kunze

CHILE: Near Valparaiso, at sea-level (19124). Vicinity of Choapa, alt. 235 meters (19457). Vicinity of Illapel, alt. 315 meters (19459).

NOTHOLAENA MOLLIS Kunze, Linnaea **9**: 54. 1834.

CHILE: Cerro Grande, vicinity of La Serena, alt. 400 meters (19301). Vicinity of Illapel, alt. 315 meters (19245). Iquique, alt. 400 meters (19451).

It seems desirable to call attention again at this place to the fact, already indicated by Mettenius,[1] that *Notholaena doradilla* Colla, as originally described and figured,[2] is identical with *N. mollis* Kunze,

[1] Abh. Senckenb. Ges. Frankfurt **3**: 74. 1859.

[2] Mem. Acad. Torino **39**: 46. *pl. 73.* 1836.

published two years earlier. Even a cursory examination of Colla's illustration should be sufficient to make clear their identity. Baker,[1] however, wrongly associated the species name of Colla with a vastly different plant from Peru, collected by the Wilkes Expedition, which departs not only in gross structural characters but very conspicuously in its large, widely imbricate, denticulate-ciliate scales of the under surface, true *N. doradilla* being densely tomentose beneath with closely mingled stellate hairs. The Peruvian plant, having never been taken up under a valid name, is here described as *Notholaena Brackenridgei,* a name given by Baker but published only as a synonym, apparently. It seems to be a rare species and, so far as the writer is aware, has been recollected only by Mr. W. E. Safford. Further particulars are given after the following description:

NOTHOLAENA BRACKENRIDGEI Baker, sp. nov.

"*Notholaena doradilla*" Baker in Hook. & Baker, Syn. Fil. 371. 1868, not Colla, 1836.

Notholaena Brackenridgei Baker, loc. cit., as synoynm.

Plants relatively large and coarse for the genus, erect, 18 to 30 cm. high. Rhizome ligneous, erect, 5 cm. high, 2 to 3 cm. thick, densely paleaceous at the summit, the scales closely impacted in an erect tuft, flaccid, linear-ligulate, 5 to 9 mm. long, 0.16 to 0.26 mm. broad at the base, sharply sinuate-flexuous in the apical half, yellowish brown, concolorous, finely lineolate (the cells very narrow, greatly elongate), distantly denticulate toward the apex. Fronds numerous, fasciculate in a peripheral crown, 15 to 28 cm. long, stiffly erect, mostly long-stipitate; stipes stout, 6 to 12 cm. long, 1 to 1.7 mm. in diameter, light brown, sublustrous, deciduously paleaceous; lamina narrowly oblong-lanceolate, 12 to 17 cm. long, 2.5 to 6 cm. broad, acuminate, slightly narrowed at the base, bipinnate-pinnatifid, the rachis stout, terete, similar to the stipe; larger pinnæ about 10 pairs, ascending (45°), petiolate, plicate in drying, the basal pair distant, subopposite, deltoid-ovate, about 3 cm. long, 2 cm. broad at the cordate base, acutish; middle pinnæ closer, larger, alternate, oblong-ovate, 2 to 4 cm. long, 1 to 2 cm. broad at the base, with 2 to 4 pairs of short-petiolate pinnules below the pinnately parted, short-acuminate tip; pinnules deltoid, the larger ones 7 to 11 mm. long, deeply pinnatifid or lobed, abruptly caudate, the lobes (2 or 3 pairs) spreading, oblong, rounded-obtuse; lower surface of the pinnæ densely paleaceous, the scales large, widely imbricate, reddish brown in mass, deltoid-

[1] Syn. Fil. 371. 1868.

oblong, long-acuminate, evenly denticulate-ciliate, nearly homogeneous in structure, the partition walls sclerotic, those of the smaller (outer) cells paler, strongly sinuate, the cells irregular; upper surface dull green, glabrescent, a few minute, lax, filiform scales evident at first along the middle; sori polycarpous, marginal, seated upon the slightly thickened ends of the oblique, once forked, pinnately arranged veins, adjacent, slightly protected by the narrowly revolute margin, the extreme border undulate-repand, slightly altered, delicately herbaceous, yellowish; sporangia confluent at maturity, glabrous; spores triplanate, coarsely tuberculate.

Type in the U. S. National Herbarium, no. 50959, collected at Baños, in the Andes of Peru, by the Wilkes Exploring Expedition; listed by Brackenridge[1] as *Notholaena sinuata* Kaulf. Agreeing with the type specimen are plants collected in the high mountains above Lima, Peru, March, 1892, by W. E. Safford (no. 999). Although these, being larger and more complete, have afforded the principal data for the above description, the Wilkes Expedition plant of Brackenridge is for other reasons selected as the nomenclatorial type.

Brackenridge's identifications of the Wilkes Expedition ferns, though made under great difficulty, were in the main correct. The present instance is a marked exception, the plant bearing no close resemblance or relationship whatever to *N. sinuata* (Swartz) Kaulf. Baker,[2] recognizing Brackenridge's error, assigned to his plant the new name *Notholaena Brackenridgei,* but apparently never published a description, merely listing it as a synonym under *Notholaena doradilla* Colla, a Chilean species with which presumably he considered it identical. *Notholaena doradilla* is, however, as may be at once noted from the illustration,[3] exactly the plant described from Chile by Kunze[4] as *N. mollis*. The Peruvian plant of Brackenridge never having been described under a valid name, the above description is offered, with the assignment of Brackenridge's specimen as the actual type because of its historical association.

Notholaena Brackenridgei might with equal propriety be placed in Cheilanthes, because of its slightly thickened fertile vein-ends and rudimentary indusia. It is one of a number of similarly intermediate species and suggests the necessity of a modern revision of this difficult and puzzling group.

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[1] In Wilkes, U. S. Explor. Exped. **16**: 19. 1854.

[2] Loc. cit.

[3] Mem. Acad. Torino **39**: 46. *pl. 73.* 1836.

[4] Linnaea **9**: 54. 1834; Farrnkr. **1**: 115. *pl. 53, f. 2.* 1843.

NOTHOLAENA AREQUIPENSIS Maxon, sp. nov.

Plants small, 6 to 10 cm. high, erect, closely tufted. Rhizomes erect or ascending, simple or branched, 1 to 2 cm. high, 1 cm. or less in diameter, coarsely radicose beneath, paleaceous above, the scales appressed, partly concealed by the persistent imbricate bases of old stipes, yellowish brown to bright castaneous in mass, linear, 3 to 5 mm. long, 0.2 to 0.4 mm. broad at the base, long-attenuate (the cells oblong to linear, thin-walled), distantly denticulate, the teeth minute, low, acutish, slightly antrorse. Fronds numerous, 5 to 8 cm. long, long-stipitate, slightly arcuate; stipes very slender, 2.5 to 5 cm. long, 0.3 to 0.5 mm. in diameter, subappressed-paleaceous, brownish beneath; lamina deltoid-oblong, 2 to 4 cm. long, 1.3 to 2.5 cm. broad, obtuse or acutish, bipinnate; pinnæ about 4 pairs, subopposite, petiolate, the basal pair the largest, distant, rounded-deltoid, 10 to 16 mm. long, 7 to 10 mm. broad, with 2 or 3 pairs of segments below the trilobate or tripartite obtuse apex, the basal segments sessile, triangular, pinnately parted or lobed, the others simpler, subsessile; second pair of pinnæ similar, slightly narrower; lower surface of the lamina (including the slender rachis) densely paleaceous, the scales large, widely imbricate, appressed, ovate-oblong, long-acuminate, light reddish brown in their lower part (the cells large, elongate-polygonal, with colored sclerotic partition walls), elsewhere pale yellowish or whitish (the sclerotic partition walls lighter, strongly sinuate), the margins deeply erose-denticulate; upper surfaces very scantily covered with the recurved attenuate apices of some of the dorsal scales, bearing also a few pale, lax, tortuous, flattish, linear scales, these mostly deciduous; sori polycarpous, exactly marginal, terminal upon the short branches of the alternate once forked veins, approximate, subcontinuous at maturity, scarcely at all concealed by the slightly revolute unaltered margin; sporangia glabrous; spores triplanate, faintly tuberculate.

Type in the U. S. National Herbarium, no. 761435, collected near Tingo, vicinity of Arequipa, Peru, altitude about 2,300 meters, August 5, 1914, by Dr. and Mrs. J. N. Rose (no. 18797).

This species, which is known to the writer also from specimens collected at Arequipa, August 8, 1901, by R. S. Williams (no. 2638), appears to be most nearly related to the plant passing as *Notholaena scariosa*. From this it differs very obviously, however, in its lesser size, the greater delicacy of all its parts, its relatively broader, almost deltoid lamina, and its absolutely unaltered margins, and in having its upper surface only laxly and very sparingly paleaceous instead

of evenly covered with stiffish, persistent, piliform, spreading scales. In general form it suggests somewhat a greatly reduced miniature of the plant here described as *N. Brackenridgei,* but it has no very near alliance with that species, being widely different in minute characters as well as in size and gross structure.

NEPHROLEPIS EXALTATA (Swartz) Schott

PERU: Cultivated at Miraflores; said to have come from eastern Peru (18670).

One of the forms included in this species as currently understood.

PELLAEA TERNIFOLIA (Cav.) Link

PERU: Vicinity of Oroya, alt. 3,700 meters (18703).

TRISMERIA TRIFOLIATA (L.) Diels

PERU: Near Santa Clara, alt. 400 meters (18736).

ASPLENIUM FRAGILE Presl

PERU: Vicinity of Oroya, alt. 3,700 meters (18702).
BOLIVIA: Vicinity of Comanche, alt. 3,800 meters (18878).

ASPLENIUM IMBRICATUM Hook. & Grev.

PERU: Vicinity of Oroya, alt. 3,700 meters (18706).

DRYOPTERIS ROSEI Maxon, sp. nov.

Rhizome erect or ascending, ligneous, closely paleaceous at the included apex, the scales large, flattish, yellowish brown, ovate or deltoid-ovate, acuminate, entire, glabrous. Fronds ascending, few, about 65 cm. long, narrow, arranged in a peripheral crown; stipes about 10 cm. long, angulate in drying, dull olivaceous, minutely puberulous with short, simple, mainly retrorse hairs; lamina linear-oblanceolate, about 55 cm. long, 10 to 12 cm. broad above the middle, long-acuminate at the apex, very gradually long-attenuate in the basal part, bipinnatifid, the pale brownish to olivaceous rachis slender (1 to 2 mm. in diameter), minutely puberulous like the stipe; pinnæ about 35 pairs, subopposite, the lowermost 12 or 13 pairs gradually shorter, the basal 3 or 4 pairs 2 to 3 cm. apart, vestigial, 1 to 3 mm. long; larger pinnæ (medial and supramedial) 1.5 to 2 cm. apart, symmetrical, narrowly linear-oblong, 5 to 6 cm. long, 9 to 12 mm. broad, sessile, slightly falcate toward the acuminate apex,

pinnatifid to within 1.5 or 2 mm. of the costa, the costa yellowish, elevated on both surfaces, sulcate above; upper leaf surface sparingly but persistently hispidulous throughout, the hairs short, antrorse, whitish, extending to and along the margins; lower leaf surface sparingly puberulous throughout, the hairs whitish, unequal, mostly patent; segments about 15 pairs below the serrate (finally subentire) apex, those of the lower two-thirds of the pinna subequal, spreading, oblong, about 4 mm. broad at the base, obtuse (more or less acutish in drying), slightly concave, the margine entire, revolute, ciliate; veins simple, 6 or 7 pairs, oblique at an angle of less than 45°, extending to the margin, slightly elevated on both surfaces, whitish; sori small, 3 to 7 pairs, medial in attachment, appearing slightly nearer the margin than the midrib; sporangia setose (setæ 0.13 to 0.19 mm. long, hyaline, acicular), the annulus 14-celled; spores diplanate, nearly smooth; indusium small, soon shrivelling, copiously whitish-ciliate. Leaf tissue firmly herbaceous, yellowish green beneath, not glandular.

Type in the U. S. National Herbarium, no. 761336, collected in the vicinity of Matucana, Peru, altitude 2,375 meters, July 9, 1914, by Dr. and Mrs. J. N. Rose (no. 18667).

Dryopteris Rosei, which is known only from the type collection, is a member of the subgenus Lastrea as redefined by Christensen[1] and, according to his treatment,[2] need be contrasted only with the rare *D. leucothrix* C. Chr.,[3] of Bolivia, the type specimen of which fortunately is available for comparison. From this *D. Rosei* differs very obviously in most characters, particularly in its shorter stipes, its shorter and narrower lamina, its shorter and much broader pinnæ (these not narrowly linear), its closer and much larger segments and more numerous veins, its shorter-ciliate indusia, its setose sporangia, and in its less pronounced hairy covering, *D. leucothrix* being densely pubescent beneath, the hairs longer and very numerous. The sporangia of *D. leucothrix* are devoid of setæ.

EQUISETACEAE

EQUISETUM BOGOTENSE H.B.K.

PERU: Vicinity of Matucana, alt. 2,375 meters (18646).
CHILE: Vicinity of La Serena (19285).

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[1] Biologiske Arbejder, tilegnede Eug. Warming, pp. 73-85. 1911.
[2] Dansk. Vid. Selsk. VII. Naturvid. Abh. **10**^{2}: 53-282. 1913.
[3] Smithsonian Misc. Coll. **52**: 377. 1909.

EQUISETUM PYRAMIDALE Goldm.

PERU: Vicinity of Lima, alt. 140 meters (18762).

SELAGINELLACEAE

SELAGINELLA PERUVIANA (Milde) Hieron.

PERU: Vicinity of Matucana, alt. 2,375 meters (19466). Near Oroya, alt. 3,700 meters (19468).

BOLIVIA: Vicinity of La Paz, alt. 3,600 meters (18845).

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AREQUIPA PYRHELIOMETRY

BY

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AREQUIPA PYRHELIOMETRY

By C. G. ABBOT[1]

In 1910 the Committee on Solar Radiation of the International Union for Cooperation in Solar Research recommended that regular observations of the intensity of solar radiation should be undertaken at additional stations in relatively cloudless regions far removed from existing stations. Prof. E. C. Pickering thereupon offered to undertake such observations at the Arequipa, Peru, station of the Harvard College Observatory if suitable apparatus should be furnished. In conversation between Messrs. Pickering and Abbot it appeared inexpedient to undertake a complete spectrobolometric program for the determination of the solar constant of radiation, but pyrheliometric observations were proposed whenever weather should permit.

By authority of the Secretary of the Smithsonian Institution, a silver disk pyrheliometer was lent for the purpose. This unfortunately was broken in transportation, and much time was lost owing to the delays of communication, so that it was not until the summer of 1912 that silver disk pyrheliometer S. I. 17 arrived at Arequipa. This instrument also was damaged in transportation, by loss of mercury from the cavity in the silver disk. But this defect was skillfully repaired by Señor J. E. Muniz.

It is probable that this alteration involved some slight change in the constant of the instrument, but probably not more than 1 per cent. Until we obtain further knowledge we may therefore retain the value of the constant as stated in " Smithsonian Pyrheliometry Revised," namely, 0.3635.

Individual measurements were made at Arequipa in the manner described in the publication just cited. The general plan of the work, as proposed by Mr. Abbot, was to secure measurements of the pyrheliometer and psychrometer at highest sun, and also at a solar zenith distance of about 70°, corresponding to three times the path in air which obtains at zenith sun. Some delay occurred in making these requirements fully understood at Arequipa, and it is to be

[1] Published by the Smithsonian Institution by request of Director E. C. Pickering of the Harvard College Observatory.

regretted that it has not generally proved practicable in connection with other duties for the observers to secure measurements with the air mass as great as 3.

At Prof. Pickering's desire the observations are reduced and published by the Smithsonian Institution. They were made at Arequipa mainly by Dr. Leon Campbell, and in part by H. Perrine. Computations are mainly by L. B. Aldrich. The position of Arequipa is: Long. $4^h\ 46^m\ 11.73^s$ W., Lat. 16° 22′ 28″ S. Alt., 2,451 meters.

Nothing would be gained by making a series of pyrheliometer measurements at a station no higher than Arequipa if such a series did not throw light on the variability of the sun or on the variability of the transparency of the earth's atmosphere. Two kinds of solar variability are thought to exist. One is associated with that general solar activity which is indicated by faculæ, sun spots, and other visible solar features. This type of variability may be expected to march in rough correlation with the eleven year sun spot cycle. Another type of solar variability appears to be of short irregular intervals in its fluctuations, which are to be measured by days or months rather than by years.

As for the variations of atmospheric transparency, we need not consider those caused by ordinary cloudiness. Pyrheliometer measurements are made only when the sky around the sun is cloudless. Water vapor and dust are the two variable elements which principally affect the atmospheric transmission of solar radiation. Water vapor is effective in two ways: it absorbs radiation of certain wave-lengths, particularly in the infra-red spectrum; and it associates itself with dust to produce haze which scatters the solar radiation of all wave-lengths, thus increasing sky light at the expense of direct sun light.

At so high a station as Arequipa, dust, except as associated with water vapor to form haze, is generally not very effective to diminish solar radiation. But after forest fires or great volcanic eruptions it may be of very great influence.

The hindrance of solar rays by the atmosphere is of course dependent on the length of path of the solar beam therein. For zenith distances (Z) less than 70° the length of atmospheric path is closely proportional to secant Z. Suppose one could observe the solar radiation outside the atmosphere, and also at the earth's surface at zenith distances whose secants were 1, 2, and 3. Let the four values of the intensity of radiation be c_0, c_1, c_2, c_3, respectively. Let the fractions $\frac{c_1}{c_0}$, $\frac{c_2}{c_1}$, $\frac{c_3}{c_2}$, be denoted by a_1, a_2, a_3, respectively. These

values may be called the atmospheric transmission coefficients at the given station for the first, second, and third air masses. As shown by Forbes and many subsequent writers, $a_1 < a_2 < a_3$, when, as with the pyrheliometer, a complex beam including many wavelengths is observed.

Confining ourselves altogether in treating of atmospheric transparency to the consideration of the quantity a_2 for the station Arequipa, as we shall do in this paper, we propose to investigate its dependence on the amount of atmospheric humidity, and on the season of the year. We hope that the observations may be continued long enough to give good correlation factors in these respects, so that in future years abnormal changes like those caused by volcanoes will reveal themselves, and their climatic influences may be studied. Remarks on the influence of the dust from the Katmai eruption of 1912 will appear below.

A second object of the work is to connect by empirical formulæ the values of intensity of solar radiation, atmospheric transmission, and humidity as observed at Arequipa with the values of the solar constant of radiation outside the atmosphere determined by the spectro-bolometer at Mount Wilson. Thus it is hoped to employ Arequipa observations to indicate variations of solar emission of radiation.

No sufficient object to justify printing all Arequipa pyrheliometer values seems to exist. We therefore abridge the results as shown in the following table. Generally observations were secured with secant *Z* values as small as 1.3, and often as small as 1.05. To give the best possible comparable values of pyrheliometer measurements, we have interpolated the values for air mass 1.2.[1] In addition we give the values for 1.0 and 2.0 air masses whenever this can be done with fair certainty. From these latter values come the transmission coefficients a_2. The humidity was determined sometimes by swinging wet and dry thermometers, sometimes by the hydrograph. We have compared results by the two methods, and have expressed all in terms of pressure of aqueous vapor in millimeters of mercury. The values given in the table are the mean values for the interval of time covered by the pyrheliometer measurements of each day. The letters *A, M,* and *P* signify morning, noon, and afternoon, respectively. In the two final columns, after the date and the initials of observers and remarks, are given empirical determinations of the solar constant of radiation, of which more will be stated hereafter.

[1] We shall use the term "air mass" in this paper as the equivalent of secant *Z,* taking no acount of barometric pressure.

TABLE 1—*Arequipa Pyrheliometry*

Date	No. of values read	Calories at air masses 1.2	1	2	Mean humidity mm.	Transmission coefficient a_2	Remarks	Observer	Solar constant Formula I	Formula II
1912										
Aug. 13 A. ...	15	1.410	.....	.....	.....	.....	Sky variable.	L. C.	.....	.....
P. ...	10	1.422	.....	.....	.....	.....	Sky variable.	L. C., H. P.	.....	.....
15 A. ...	8	1.434	1.474	1.273	.....	.864	Sky clear.	L. C.	.....	.....
P. ...	20	1.452	1.493	1.290	.....	.865	Sky clear.	L. C., H. P.	.....	.....
16 A. ...	6	1.440	.....	.....	.....	.....	Windy.	L. C., H. P.	.....	.....
P. ...	15	1.456	1.518	1.210	.....	.797	Sky clear.	L. C., H. P.	.....	.....
17 P. ...	15	1.417	1.470	1.200	.....	.817	Sky 0-1.	L. C., H. P.	.....	.....
19 A. ...	6	1.533	.....	.....	.....	.....	Sky 2-1.	L. C., H. P.	.....	.....
P. ...	6	1.570	.....	.....	.....	.....	Windy, slight haze.	L. C., H. P.	.....	.....
20 A. ...	4	1.465	.....	.....	.....	.....	Haze, sky 1-2.	L. C., H. P.	.....	.....
P. ...	7	1.440	.....	.....	.....	.....	Clouds very near.	L. C., H. P.	.....	.....
22 A. ...	6	1.503	.....	.....	.....	.....	Sky 2-3, sun clear.	L. C., H. P.	.....	.....
P. ...	10	1.500	1.532	1.368	.....	.894	Sky 2-3, sun clear.	L. C., H. P.	.....	.....
23 A. ...	5	1.463	.....	.....	.....	.....	Sky clear, 1-2.	L. C., H. P.	.....	.....
P. ...	6	1.483	.....	.....	.....	.....	Sky clear, 1-2.	L. C., H. P.	.....	.....
24 A. ...	6	1.484	.....	.....	.....	.....	Windy, sky 2.	L. C., H. P.	.....	.....
P. ...	2	1.467	.....	.....	.....	.....	Sky 2.	L. C., H. P.	.....	.....
28 A. ...	3	1.540	.....	.....	.....	.....	Sky 0.	L. C.	.....	.....
P. ...	6	1.540	.....	.....	.....	.....	Windy, sky 0.	H. P.	.....	.....
29 A. ...	5	1.540	.....	.....	.....	.....	Sky 0.	L. C., H. P.	.....	.....
P. ...	5	1.540	.....	.....	.....	.....	Sky 0.	L. C., H. P.	.....	.....
30 A. ...	4	1.535	.....	.....	.....	.....	Sky 0.	L. C.	.....	.....
P. ...	4	1.518	.....	.....	.....	.....	Sky 0, windy.	L. C.	.....	.....
31 A. ...	4	1.497	.....	.....	.....	.....	Sky 0.	L. C., H. P.	.....	.....
P. ...	6	1.517	.....	.....	.....	.....	Sky 0, windy.	H. P.	.....	.....
Sept. 1 A. ...	2	1.493	.....	.....	.....	.....	Sky 0, windy.	L. C.	.....	.....
2 A. ...	6	1.504	1.557	1.300	.....	.835	Sky 0.	L. C.	.....	.....
P. ...	2	1.497	.....	.....	.....	.....	Sky 0.	L. C.	.....	.....
3 A. ...	3	1.512	.....	.....	.....	.....	Sky 0.	L. C.	.....	.....
P. ...	4	1.512	.....	.....	.....	.....	Sky 0, windy.	L. C.	.....	.....

TABLE I—*Arequipa Pyrheliometry* (Continued)

Date		No. of values read.	Calories at air masses 1.2	1	2	Mean humidity mm.	Trans-mission coefficient a_2	Remarks	Observer	Solar constant Formula I	Formula II
Sept.	4 A. ...	3	1.488	.....	.....	.....	.....	Sky 0-1.	L. C.	.....	.....
	P. ...	4	1.488	.....	.....	.....	.....	Sky 1.	L. C.	.....	.....
	5 A. ...	2	1.450	.....	.....	.....	.....	....	L. C.	.....	.....
	P. ...	5	1.450	.....	.....	.....	.....	Sky 2.	H. P., L. C.	.....	.....
	6 A. ...	2	1.498	.....	.....	.....	.....	Sky 1.	L. C.	.....	.....
	P. ...	4	1.498	.....	.....	.....	.....	Sky 1.	L. C.	.....	.....
	7 A. ...	2	.....	.....	.....	.....	.....	Sky 4.	H. P.	.....	.....
	P. ...	4	1.520	.....	.....	.....	.....	Sky 3.	H. P.	.....	.....
	8 A. ...	2	1.462	.....	.....	.....	.....	Windy, sky 2.	L. C.	.....	.....
	P. ...	4	1.462	.....	.....	.....	.....	Windy, sky 2.	L. C.	.....	.....
	9 A. ...	4	1.490	.....	.....	.....	.....	Sky 1.	L. C.	.....	.....
	P. ...	4	1.490	.....	.....	.....	.....	Sky 1.	L. C., H. P.	.....	.....
	10 P. ...	6	1.537	.....	.....	.....	.....	Sky 0.	L. C.	.....	.....
	11 P. ...	6	1.448	.....	.....	.....	.....	Sky 1-2.	H. P., L. C.	.....	.....
	12 P. ...	6	1.495	.....	.....	.....	.....	Sky 0.	L. C.	.....	.....
	13 A. ...	6	1.512	.....	.....	.....	.....	Sky 1, hazy.	L. C.	.....	.....
	14 P. ...	5	1.522	.....	.....	.....	.....	Sky 0.	L. C.	.....	.....
	15 A. ...	6	1.522	.....	.....	.....	.....	Sky 0.	L. C.	.....	.....
	16 A. ...	6	1.495	.....	.....	.....	.....	Sky 0.	L. C.	.....	.....
	17 A. ...	6	1.480	.....	.....	.....	.....	Sky clear.	L. C.	.....	.....
	18 A. ...	5	1.486	.....	.....	.....	.....	Sky 0, windy.	L. C.	.....	.....
	19 A. ...	6	1.468	.....	.....	.....	.....	Sky 2.	L. C.	.....	.....
	20 A. ...	6	1.494	.....	.....	.....	.....	Sky 5, clear near sun.	L. C.	.....	.....
	22 A. ...	6	1.480	.....	.....	.....	.....	Sky 4, clear near sun.	L. C.	.....	.....
	24 A. ...	8	1.423	1.483	1.194	.....	.806	Sky 1-2.	L. C.	.....	.....
	25 A. ...	7	1.412	.....	.....	.....	.....	Sky 2.	L. C.	.....	.....
	27 A. ...	4	1.457	.....	.....	.....	.....	Sky 3, sky variable.	L. C.	.....	.....
	30 A. ...	6	1.522	.....	.....	.....	.....	Sky 2.	L. C.	.....	.....
Oct.	1 A. & P.	10	1.513	.....	.....	.....	.....	Sky 0, P. M. better.	L. C.	.....	.....
	2 A. ...	5	1.513	.....	.....	.....	.....	Sky 1.	L. C.	.....	.....
	3 M. .	4	1.571	.....	.....	.....	.....	Sky scattered cirri, but thin.	L. C.	.....	.....

TABLE I—*Arequipa Pyrheliometry* (Continued)

Date	No. of values read	Calories at air masses			Mean humidity mm.	Trans-mission coefficient a_2	Remarks	Observer	Solar constant	
		1.2	1	2					Formula I	Formula II
Oct. 6 M.	5	1.503	.....	.....	.....	.....	Sky 4.	L. C.	.....	.....
8 A.	10	1.540	.....	.....	.....	.....	Sky 1-2.	L. C.	.....	.....
P.	12	1.540	.....	.....	.....	.....	Sky 1, hazy.	L. C.	.....	.....
9 A.	33	1.536	1.561	1.436	.....	.920	Sky 0-1-2, hazy.	L. C.	.....	.....
P.	20	1.497	1.541	1.316	.....	.854	Sky 0-1, slight haze.	L. C.	.....	.....
10 A.	11	1.552	1.581	1.438	.....	.910	Sky 0.	L. C.	.....	.....
11 A.	9	1.583	.....	.....	.....	.....	Sky 0, exceptionally clear.	L. C.	.....	.....
12 A.	6	1.609	.....	.....	.....	.....	Exceptionally clear.	L. C.	.....	.....
13 M.	6	1.586	.....	.....	.....	.....	Sky 1.	L. C.	.....	.....
14 A.	5	1.614	.....	.....	.....	.....	Sky very clear.	L. C.	.....	.....
15 A.	8	1.600	.....	.....	.....	.....	Sky very clear.	L. C.	.....	.....
16 M.	5	1.577	.....	.....	.....	.....	Sky 0.	L. C.	.....	.....
17 M.	7	1.624	.....	.....	.....	.....	Sky 0.	H. P., L. C.	.....	.....
18 A.	5	1.560	.....	.....	.....	.....	Sky 1.	L. C.	.....	.....
19 A.	10	1.578	.....	.....	.....	.....	Sky 2-1.	H. P., L. C.	.....	.....
20 M.	5	1.549	.....	.....	.....	.....	Sky 0-1.	L. C.	.....	.....
21 A.	22	1.561	1.590	1.440	.....	.906	Sky 0.	L. C.	.....	.....
P.	8	1.516	1.595?	1.200?	.....	.755?	Sky 0, then windy and dust in air.	L. C.	.....	.....
22 M.	5	1.564	.....	.....	.....	.....	Sky 1.	L. C.	.....	.....
23 M.	5	1.550	.....	.....	.....	.....	Sky 0, hazy near horizon.	L. C.	.....	.....
24 M.	5	1.562	.....	.....	.....	.....	Sky 4.	H. P.	.....	.....
Nov. 4 P.	5	1.540	.....	.....	.....	.....	Sky 1, sun clear.	L. C.	.....	.....
9 A.	5	1.521	.....	.....	.....	.....	Sky 2.	L. C.	.....	.....
18 M.	5	1.529	.....	.....	.....	.....	Sky 2.	H. P.	.....	.....
19 M.	5	1.585	.....	.....	.....	.....	Sky 4.	H. P.	.....	.....
20 M.	5	1.570	.....	.....	.....	.....	Sky 0, slight haze.	L. C.	.....	.....
21 M.	5	1.527	.....	.....	.....	.....	Sky 0.	L. C.	.....	.....
25 A.	6	1.554	.....	.....	3.00	.....	Sky 1.	L. C.	1.87	.....

TABLE I—*Arequipa Pyrheliometry* (Continued)

Date	No. of values read	Calories at air masses 1.2	1	2	Mean humidity mm.	Transmission coefficient a_2	Remarks	Observer	Solar constant Formula I	Formula II
Dec. 4 A. ...	6	1.528	.....	.....	6.76	.....	Sky 2.	L. C.	1.94	.....
6 A. ...	4	1.534	.....	.....	8.19	.....	Sky 3.	L. C.	1.98	.....
11 A. ...	12	1.490	1.546	1.270	6.88	.821	Sky 2.	L. C.	1.90	1.92
12 A. ...	10	1.555	1.583	1.443	8.04	.912	Sky 0-1.	L. C.	2.00	1.96
P. ...	4	1.542	1.603	1.300	(8.00)	.811	Sky 4.	H. P.	1.99	2.03
15 A. ...	8	1.470	.....	.....	5.79	.....	Sky 3-4, then clouds.	H. P.	1.85	.....
1913										
Jan. 3 A. ...	6	1.443	1.470	1.334	8.26	.907	Sky 3-5, then clouds.	L. C.	1.86	1.82
4 A. ...	10	1.390	1.450	1.143	10.20	.788	Sky 4, sun clear.	L. C.	1.82	1.91
6 A. ...	12	1.526	1.571	1.349	8.64	.859	Sky 3-2-1.	L. C.	1.98	1.99
8 A. ...	4	1.500	.....	.....	8.33	.....	Sky 3.	H. P.	1.94	.....
10 A. ...	6	1.486	.....	.....	9.32	.....	Sky 2.	L. C.	1.93	.....
Feb. 4 P. ...	4	1.464	.....	.....	9.65	.....	Sky 1, windy.	L. C.	1.92	.....
Mar. 24 A. ...	16	1.321	1.362	1.150	8.00	.845	Sky 2-2-3, hazy.	L. C.	1.75	.....
Apr. 1 A. ...	10	1.387	1.427	1.230	7.90	.862	Sky 2, then 5.	L. C.	1.84	1.84
2 A. ...	10	1.393	1.450	1.172	7.25	.808	Sky 3.	L. C.	1.84	1.88
7 A. ...	12	1.430	1.478	1.237	8.90	.836	Sky 0.	L. C.	1.92	1.96
9 A. ...	10	1.394	1.431	1.243	8.75	.869	Sky 4-5, then cloudy.	L. C.	1.87	1.87
25 P. ...	10	1.439	1.474	1.298	5.07	.881	Sky 1.	L. C.	1.88	1.90
30 P. ...	2	1.430	.....	.....	(3.5)?	.....	Sky 2, then clouds.	L. C.	1.80?	.....
May 1 A. ...	6	1.330	1.371	1.160	(3.7)?	.846	Sky 1, then clouds.	L. C.	1.70?	.....
4 A. ...	12	1.518	1.568	1.320	3.90	.842	Sky 0.	L. C.	1.94	1.96
5 A. ...	12	1.508	1.530	1.419	3.80	.927	Sky 0.	L. C.	1.92	1.88
6 P. ...	12	1.525	1.571	1.342	4.72	.854	Sky 0.	L. C.	1.98	1.98
7 P. ...	8	1.473	1.510	1.321	5.99	.875	Sky 2.	L. C.	1.95	1.92
8 P. ...	12	1.480	1.515	1.346	4.61	.889	Sky 2.	L. C.	1.92	1.89
10 A. ...	12	1.494	.....	.....	3.78	.....	Sky 2.	L. C.	1.90	.....
11 A. ...	12	1.506	1.543	1.353	4.47	.877	Sky 2.	L. C.	1.95	1.94
13 A. ...	12	1.465	1.510	1.283	5.48	.850	Sky 2-1.	L. C.	1.94	1.93
21 A. ...	8	1.473	.....	.....	5.27	.....	Sky gen. clear.	L. C.	1.94	.....

TABLE 1—*Arequipa Pyrheliometry* (Continued)

Date	No. of values read	Calories at air masses			Mean humidity mm.	Transmission coefficient a_2	Remarks	Observer	Solar constant	
		1.2	1	2					Formula I	Formula II
May 23 A. ...	5	1.463	.....	.....	(3.00)	.....	Sky 2.	L. C.	1.84?	.....
24 A. ...	8	1.490	1.510	1.417	2.74	.939	Sky clear.	L. C.	1.86	1.83
June 2 A. ...	8	1.497	.....	.....	3.12	.....	Sky 1.	L. C.	1.90	.....
3 P. ...	6	1.560	1.598	1.408	2.74	.881	Sky clear.	L. C.	1.95	1.97
4 P. ...	10	1.583	1.630	1.393	4.00	.855	Sky 1.	L. C.	2.04	2.05
13 P. ...	4	1.468	.....	.....	4.79	.....	Sky 1, then clouds.	L. C.	1.93	.....
14 A. ...	6	1.403	1.453	1.203	4.22	.829	Sky 3, windy.	L. C.	1.84	1.86
15 A. ...	4	1.416	1.454	1.260	3.81	.868	Sky ?	L. C., H. P.	1.84	1.84
16 P. ...	6	1.434	1.469	1.297	5.72	.883	Sky 2, hazy.	L. C.	1.92	1.89
17 P. ...	6	1.489	1.527	1.338	4.56	.875	Sky 4, then clear.	L. C.	1.95	1.94
18 P. ...	4	1.497	1.530	1.367	3.76	.894	Sky 0.	L. C.	1.94	1.92
19 P. ...	4	1.483	1.513	1.356	4.42	.896	Sky 0.	L. C.	1.94	1.91
24 P. ...	4	1.597	1.635	1.440	3.30	.882	Sky 0, some haze.	L. C.	2.04	2.03
25 P. ...	4	1.567	1.613	1.380	2.23	.856	Sky 0.	L. C.	1.94	2.00
26 P. ...	4	1.540	1.578	1.398	3.04	.886	Sky 0.	L. C.	1.96	1.98
27 A. ...	6	1.522	1.550	1.410	2.85	.910	Sky 1, windy and dusty.	L. C.	1.92	1.91
28 A. ...	4	1.460	1.485	1.357	3.07	.915	Sky 2, hazy from near volcano.	L. C.	1.86	1.84
July 1 A. ...	4	1.460	1.498	1.312	4.20	.875	Hazy.	L. C.	1.91	1.90
2 P. ...	4	1.505	1.550	1.326	3.00	.856	Sky 1.	L. C.	1.91	1.94
3 M. .	2	1.397	.....	.....	5.38	.....	Sky 1, windy.	L. C.	1.86	.....
7 P. ...	4	1.480	1.512	1.352	2.70	.895	Sky clear.	L. C.	1.86	1.87
8 P. ...	4	1.491	1.520	1.371	2.25	.902	Sky clear.	L. C.	1.85	1.87
13 P. ...	2	1.463	.....	.....	2.20	.....	Sky 0.	L. C.	1.82	.....
14 P. ...	4	1.476	1.510	1.339	2.55	.887	Sky 0.	L. C.	1.85	1.87
15 P. ...	4	1.486	1.560	1.192	2.05	.764	Sky 1, hazy.	H. P., L. C.	1.83	1.97
17 A. & P.	6	.....	.....	.....	2.50	.....	Sky 1-0.	L. C.	.....	.....
18 P. ...	4	1.504	1.530	1.400	3.00	.915	Sky 0.	L. C.	1.91	1.87
19 A. ...	6	1.451	1.479	1.345	3.00	.909	Sky 1, windy.	L. C.	1.85	1.83
20 A. ...	2	.....	.....	.....	2.68	.....	Sky 2, then clouds.	L. C.	.....	1.89

TABLE I—*Arequipa Pyrheliometry* (Continued)

Date	No. of values read	Calories at air masses 1.2	1	2	Mean humidity mm.	Transmission coefficient a_2	Remarks	Observer	Solar constant Formula I	Formula II
July 22 P. ...	4	1.450	1.491	1.282	4.01	.860	Sky 1, clear.	L. C.	1.89	1.83
25 P. ...	4	1.436	1.470	1.298	2.91	.883	Sky 1.	L. C.	1.82	.....
26 P. ...	4	1.452	1.490	1.300	2.95	.873	Sky 1.	L. C.	1.85	1.86
27 P. ...	2	1.474	.....	.....	3.53	.....	Sky 1, then clouds.	L. C.	1.90	.....
29 P. ...	6	1.511	1.550	1.357	3.44	.876	Sky 0.	L. C.	1.94	1.94
30 P. ...	4	1.520	1.563	1.347	3.08	.862	Sky clear.	L. C.	1.93	1.95
31 P. ...	4	1.432	1.463	1.310	2.95	.897	Sky 1.	L. C.	1.82	1.82
Aug. 4 P. ...	4	1.540	1.586	1.340	3.55	.845	Sky clear.	L. C.	1.98	2.01
5 P. ...	4	1.550	1.590	1.408	2.94	.886	Sky 2-1.	L. C.	1.95	.....
6 P. ...	4	1.481	1.524	1.309	3.14	.859	Sky clear.	L. C., H. P.	1.88	1.90
7 P. ...	4	1.518	1.565	1.333	2.65	.852	Sky clear.	L. C.	1.90	.....
8 P. ...	4	1.334	1.380	1.155	3.30	.837	Very hazy and dusty	L. C.	1.70	.....
12 P. ...	4	1.457	1.496	1.297	4.25	.867	Sky 1, sun clear.	L. C	1.89	1.89
13 P. ...	2	1.403	.....	.....	3.79	.....	Sky 3, then clouds.	L. C.	1.81	.....
14 P. ...	4	1.428	1.467	1.254	3.60	.854	Sky 2, clouds near.	L. C.	1.83	1.85
15 P. ...	4	1.439	1.477	1.279	3.96	.866	Sky 1.	L. C.	1.85	1.85
16 A. ...	4	1.390?	.....	.....	5.78	.....	Sky 2.	C. W.	1.84?	.....
17 A. ...	4	1.348	1.392	1.168	4.57	.839	Sky 6.	C. W.	1.76	1.77
18 P. ...	4	1.500	1.530	1.361	6.05	.890	Sky 0.	H. P.	1.99	1.96
21 P. ...	2	1.568	.....	.....	1.60(?)	.....	Sky 3, then clouds.	L. C.	1.86	.....
22 P. ...	2	1.503	.....	.....	3.11	.....	Sky 8.	?	1.88	.....
25 P. ...	2	1.452	.....	.....	5.20	.....	Sky 1.	L. C.	1.90	.....
26 P. ...	4	1.442	1.493	1.227	4.16	.822	Sky 1.	L. C.	1.85	1.88
27 P. ...	4	1.427	1.469	1.262	5.14	.859	Sky 1.	L. C.	1.86	1.86
28 P. ...	2	1.423	.....	.....	5.58	.....	Sky 3.	L. C.	1.87	.....
30 P. ...	2	1.483	.....	.....	6.25	.....	Sky 3.	L. C.	1.96	.....
Sept. 1 A. ...	4	1.438	1.495	1.206	4.46	.808	Sky 1.	L. C.	1.85	1.89
2 P. ...	4	1.452	1.510	1.247	4.05	.826	Sky 1.	L. C.	1.85	1.88
3 P. ...	4	1.525	1.579	1.306	4.56	.827	Sky clear.	L. C., H. P.	1.96	2.00
4 P. ...	4	1.495	1.523	1.373	4.30	.902	Sky 0-1.	L. C.	1.91	1.89
8 P. ...	4	1.528	1.570	1.363	3.91	.869	Sky 0.	L. C.	1.94	1.95

TABLE I—*Arequipa Pyrheliometry* (Continued)

Date	No. of values read.	Calories at air masses 1.2	1	2	Mean humidity mm.	Transmission coefficient a_2	Remarks	Observer	Solar constant Formula I	Formula II
Sept. 9 P. ...	4	1.500	1.567	1.224	4.31	.781	Sky 0, then hazy and very dusty.	L. C.	1.92	1.99
10 P. ...	4	1.452	1.498	1.278	3.87	.853	Sky 2.	L. C.	1.84	1.84
12 P. ...	2	1.474	.....	.....	3.81	.....	Sky 1.	L. C.	1.86	.....
17 P. ...	4	1.514	1.547	1.384	3.75	.894	Sky 0.	L. C.	1.91	1.89
18 P. ...	4	1.483	1.537	1.270	3.91	.827	Sky 0.	L. C.	1.88	1.91
21 P. ...	2	1.402	.....	.....	3.79	.....	Sky 1.	L. C.	1.77	.....
22 P. ...	4	1.499	1.535	1.357	4.74	.884	Sky 1-0.	L. C.	1.92	1.90
23 P. ...	4	1.543	1.588	1.357	4.64	.854	Sky 0.	L. C.	1.98	1.98
26 P. ...	4	1.406	1.447	1.249	6.41	.864	Sky 1, clear.	L. C.	1.84	1.83
27 P. ...	4	1.440	1.485	1.261	6.93	.849	Sky 1.	L. C.	1.89	1.90
28 P. ...	4	1.515	1.563	1.324	7.12	.847	Sky 1, clear.	L. C.	2.00	2.00
29 P. ...	4	1.500	1.535	1.356	6.67	.883	Sky 0-1.	H. P.	1.97	1.93
30 P. ...	4	1.447	1.498	1.238	6.41	.826	Sky 1, very windy.	H. P., L. C.	1.89	1.91
Oct. 1 P. ...	4	1.435	1.500	1.178	5.25	.785	Sky 2.	L. C.	1.84	1.90
2 P. ...	6	1.471	1.510	1.305	4.70	.864	Sky (?).	H. P., C. W.	1.88	1.87
3 P. ...	4	1.443	1.485	1.273	5.08	.857	Sky 1.	L. C.	1.85	1.85
4 P. ...	4	1.438	1.488	1.245	5.43	.836	Sky 1, clear, windy.	L. C.	1.86	1.86
6 P. ...	4	1.480	1.530	1.280	4.97	.836	Sky 1.	L. C.	1.89	1.90
18 P. ...	4	1.440	.....	.....	6.64	.....	Sky 5-4.	H. P., L. C.	1.87	.....
20 P. ...	2	1.418	.....	.....	6.68	.....	Sky (?).	H. P.	1.84	.....
21 A. ...	2	1.302	.....	.....	5.54	.....	Sky 4, variable.	L. C.	1.66	.....
22 A. ...	2	1.408	.....	.....	5.91	.....	Sky 5.	L. C.	1.81	.....
23 P. ...	2	1.330	.....	.....	7.31	.....	Sky 3.	L. C.	1.73	.....
25 A. ...	4	1.458	.....	.....	7.71	.....	Sky 1-2.	L. C.	1.90	.....
29 A. ...	4	1.403	.....	.....	6.55	.....	Sky 2.	L. C.	1.81	.....
31 A. ...	4	1.496	1.563	1.225	6.18	.780	Sky 2.	L. C.	1.92	1.98
Nov. 1 P. ...	2	1.535	.....	.....	5.07	.....	Sky 2.	L. C.	1.94	.....
8 A. ...	2	1.495	.....	.....	5.44	.....	Sky 2.	L. C.	1.89	.....
14 P. ...	2	1.470	.....	.....	5.80	.....	Sky 5, windy.	H. P.	1.87	.....
16 A. ...	2	1.468	.....	.....	6.86	.....	Sky 4.	L. C.	1.88	.....

TABLE 1—*Arequipa Pyrheliometry* (Continued)

Date	No. of values read	Calories at air masses			Mean humidity mm.	Transmission coefficient a_2	Remarks	Observer	Solar constant	
		1.2	1	2					Formula I	Formula II
Nov. 17 A. ...	4	1.429	.....	.....	8.50	.....	Sky 4-6.	L. C.	1.86	.....
18 A. ...	4	1.479	.....	.....	6.54	.....	Sky 4-3.	L. C.	1.89	.....
25 A. ...	2	1.560	.....	.....	7.61	.....	Sky 2.	L. C.	2.01	.....
26 A. ...	4	1.525	.....	.....	7.82	.....	Sky 1-3, windy.	L. C., H. P.	1.97	.....
27 A. ...	6	1.507	1.563	1.277	6.55	.817	Sky 1-2.	L. C.	1.92	1.95
28 P. ...	4	1.502	1.551	1.300	6.50	.838	Sky 3.	L. C.	1.92	1.93
29 A. ...	4	1.530	.....	.....	6.48	.....	Sky clear 3, windy.	L. C., H. P.	1.95	.....
30 P. ...	4	1.538	1.577	1.380	7.27	.875	Sky 4-3.	L. C.	1.98	1.96
Dec. 1 A. & P.	6	1.570	1.613	1.389	5.78	.861	Sky 0-1.	L. C.	1.98	1.96
2 A. & P.	6	1.565	1.607	1.397	5.00	.869	Sky 0.	L. C., H. P.	1.95	1.93
3 P. ...	4	1.515	1.569	1.303	6.02	.830	Sky 2-3, very windy.	L. C.	1.91	1.93
11 A. & P.	6	1.550	1.609	1.307	5.70	.812	Sky clear, 2.	L. C.	1.95	1.98
12 A. & P.	6	1.521	1.597	1.228	5.00	.768	Sky 2, clear.	L. C.	1.89	1.96
13 P. ...	2	1.487	.....	.....	7.56	.....	Sky 4.	L. C.	1.91	.....
14 A. & P.	4	1.515	.....	.....	6.78	.....	Sky 1-2.	L. C.	1.93	.....
17 A. ...	4	1.471	.....	.....	7.88	.....	Sky 3, windy.	L. C.	1.89	.....
19 P. ...	2	1.507	.....	.....	6.58	.....	Sky 5, windy.	H. P.	1.92	.....
20 A. & P.	4	1.520	.....	.....	11.18	.....	Sky 1, windy.	H. P.	2.01	.....
21 A. & P.	4	1.540?	.....	.....	12.70	.....	Sky 1-3, windy.	L. C., H. P.	2.05?	.....
23 A. ...	2	1.465	.....	.....	8.20	.....	Sun clear.	H. P.	1.89	.....
28 A. & P.	8	1.490	1.547	1.262	7.77	.816	Sky 2-4-3, windy.	H. P., L. C.	1.92	1.95
29 A. & P.	4	1.532	.....	.....	5.98	.....	Sky 0-1.	H. P.	1.92	.....
30 A. & P.	6	1.521	1.570	1.323	6.42	.843	Sky 2-3, windy.	C. W., H. P.	1.93	1.93
1914										
Jan. 2 A. & P.	6	1.506	.....	.....	8.01	.....	Sky 1-0-2.	H. P., C. W.	1.94	.....
3 A. & P.	6	1.560?	1.627?	1.300?	5.96	.799	Sky 1-4, very windy.	C. W., H. P.	1.97?	2.01
6 A. ...	6	1.473	1.518	1.297	6.00	.854	Sky 6-5-5.	L. C., C. W., H. P.	1.86	1.85
10 A. ...	2	1.496	.....	.....	9.57	.....	Sky 6.	H. P.	1.95	.....
11 A. ...	4	1.520	.....	.....	8.29	.....	Sky 4-3.	H. P., L. C.	1.96	.....

TABLE 1—*Arequipa Pyrheliometry* (Continued)

Date	No. of values read	Calories at air masses			Mean humidity mm.	Trans-mission coefficient a_2	Remarks	Observer	Solar constant	
		1.2	1	2					Formula I	Formula II
Jan. 12 A. & P.	6	1.465	1.515	1.260	5.31(?)	.832	Sky 0-2-4, windy.	H. P.	1.83?	1.84
15 A. ...	8	1.574	1.615	1.410	6.36	.873	Sky clear, windy.	L. C.	2.00	1.97
20 A. ...	2	1.427	.....	.....	8.30	.....	Sky 6.	L. C.	1.84	.....
21 A. ...	4	1.461	1.512	1.259	9.23	.833	Sky 1-2.	L. C.	1.90	1.94
29 A. ...	4	1.503	1.537	1.376	5.95	.....	Sky 3.	L. C.	1.89	.....
30 A. ...	2	1.460	.....	.....	7.90	.....	Sky 4.	L. C.	1.88	.....
Feb. 2 A. ...	3	1.420	1.450	1.303	9.42	.889	Sky 4-5.	L. C.	1.86	1.85
9 A. ...	2	1.455	.....	.....	9.99	.....	Sky 4.	L. C.	1.91	.....
12 A. ...	4	1.455	.....	.....	10.27	.....	Sky 5-4.	H. P., L. C.	1.92	.....
13 A. ...	6	1.484	.....	.....	10.27	.....	Sky 5, then clearer.	L. C.	1.96	.....
14 A. ...	4	1.470	.....	.....	9.74	.....	Sky 4-3.	L. C.	1.93	.....
15 A. ...	4	1.468	.....	.....	9.19	.....	Sky 2-4.	H. P.	1.92	.....
16 A. ...	4	1.440	1.500	1.260	9.72	.840	Sky 3-2.	L. C.	1.90	1.94
18 A. ...	4	1.456	1.500	1.282	10.95	.855	Sky 4-6.	L. C.	1.94	1.98
19 A. ...	2	.....	.....	.....	10.11	.....	Sky 3.	L. C.	.....	.....
23 A. ...	4	1.520?	.....	.....	7.71	.....	Sky 1.	L. C.	1.98?	.....
24 A. ...	4	1.480	.....	.....	8.87	.....	Sky 1.	L. C.	1.94	.....
27 A. ...	2	1.450	.....	.....	9.09	.....	Sky 5.	L. C.	1.92	.....
Mar. 3 A. ...	4	1.511	.....	.....	7.64	.....	Sky 5-3.	L. C.	1.97	.....
5 A. ...	4	1.560	.....	.....	13.08	.....	Sky 5.	L. C.	2.11	.....
6 A. ...	6	1.500	1.537	1.344	7.39	.874	Sky 4-3-2.	L. C.	1.96	1.94
7 A. ...	4	1.539	1.578	1.383	.816	.876	Sky 2.	L. C.	2.03	2.01
10 A. ...	4	1.440	1.470	1.320	8.16	.898	Sky 2.	L. C.	1.84	1.87
15 A. ...	4	1.454	1.473	1.377	8.57	.935	Sky clear, 1.	L. C.	1.92	1.86
16 A. ...	4	1.482	1.532	1.288	8.07	.841	Sky clear.	L. C.	1.96	1.98
18 A. ...	6	1.440	1.460	1.360	8.25	.931	Sky 2.	L. C.	1.91	1.85
19 A. ...	2	.....	.....	.....	8.74	.....	Sky 2.	L. C.	.....	.....
22 P. ...	2	1.428	.....	.....	9.05	.....	Sky 3.	L. C.	1.91	.....
25 A. ...	4	1.438	.....	.....	9.27	.....	Sky 2.	L. C.	1.92	.....
26 A. ...	4	1.427	1.468	1.270	8.93	.865	Sky 4-6.	H. P.	1.91	1.90
27 A. ...	4	1.459	1.502	1.285	4.87	.855	Sky 2.	L. C.	1.87	1.86

TABLE 1—*Arequipa Pyrheliometry* (Continued)

Date	No. of values read	Calories at air masses 1.2	1	2	Mean humidity mm.	Trans-mission coefficient a_2	Remarks	Observer	Solar constant Formula I	Formula II
Mar. 28 A. ...	4	1.473	1.505	1.340	8.28	.890	Sky 2-3.	L. C.	1.96	1.94
30 A. ...	8	1.465	1.495	1.343	8.02	.897	Sky 3-2.	L. C.	1.95	1.92
31 A.&P.	6	1.440	.....	.....	7.48	.....	Sky 2-2-5.	L. C.	1.90	.....
Apr. 4 A. ...	6	1.453	1.480	1.344	6.60	.908	Sky hazy, 2-2-3.	L. C., H. P.	1.91	1.86
5 A.&P.	10	1.489	1.525	1.344	6.48	.882	Sky 3-0-0-1-1.	L. C., H. P.	1.95	1.92
6 A. ...	4	1.487	1.510	1.392	6.29	.922	Sky 0.	H. P.	1.95	1.89
7 P. ...	2	1.480	.....	.....	7.84	.....	Sky 2.	L. C.	1.97	.....
8 A. ...	4	1.488	1.517	1.386	6.22	.914	Sky 3.	H. P., L. C.	1.95	1.90
10 A. ...	4	1.500	1.548	1.310	6.48	.846	Sky 2.	L. C.	1.97	1.97
11 A. ...	5	1.442	1.484	1.280	7.33	.867	Sky 1-1-4.	L. C., H. P.	1.91	1.90
12 A. ...	4	1.492	.....	.....	5.70	.....	Sky 4-3.	H. P.	1.94	.....
14 P. ...	4	1.479	1.554	1.177	(6.00)?	.....	Sky 2-1.	L. C., H. P.	(1.93)?	.....
15 A.&P.	4	.....	.....	.....	7.65	.....	Sky 2-2.	H. P., L. C.	.....	.....
16 P. ...	2	1.494?	.....	.....	(6.00)?	.....	Sky 1.	?	(1.95)?	.....
17 P. ...	4	1.454	1.477	1.368	7.35	.926	Sky 1-2, windy.	L. C., H. P.	1.93	1.87
22 P. ...	4	1.507	1.547	1.350	(6.00)?	.872	Sky 0.	H. P.	(1.98)?	1.96
25 A. ...	4	1.510	.....	.....	5.33	.....	Sky 0.	H. P., L. C.	1.97	.....
26 P. ...	4	1.522	1.573	1.315	6.03	.836	Sky 0.	L. C.	2.00	2.01
May 4 P. ...	4	1.430	1.496	1.180	7.21	.....	Sky 2-5, very windy and dusty.	L. C., H. P.	1.92	.....
5 P. ...	2	1.440?	.....	.....	8.49	.....	Sky 3.	H. P.	1.95?	.....
6 P. ...	2	1.473?	.....	.....	7.57	.....	Sky 2.	H. P.	1.98?	.....
7 P. ...	4	1.456	1.490	1.320	6.27	.886	Sky 3-5, windy.	L. C.	1.93	1.91
11 A. ...	4	1.434	1.470	1.290	6.48	.878	Sky 1.	L. C.	1.92	1.89
12 P. ...	4	1.474	.....	.....	(6.00)?	.....	Sky (?)	L. C.	(1.96)?	.....
13 *	....	.....	.....	.....	.....	.....	......	.....	.....	.....
June 12 P. ...	2	1.460?	.....	.....	5.62	.....	Sky 3.	L. C.	1.95?	.....
16 P. ...	4	1.547	1.588	1.380	3.75	.869	Sky 0, windy.	H. P.	2.00	2.00
18 P. ...	4	1.421	1.441	1.352	(4.66)?	.937	Sky 1, hazy, windy.	L. C., H. P.	(1.87)?	1.81
19 A.&P.	4	1.472	.....	.....	4.54	.....	Sky 2-3.	H. P.	1.93	.....

* Pyr. sent to be overhauled if necessary.

TABLE I—*Arequipa Pyrheliometry* (Continued)

Date	No. of values read	Calories at air masses			Mean humidity mm.	Trans-mission coefficient a_2	Remarks	Observer	Solar constant	
		1.2	1	2					Formula I	Formula II
June 20 A. ...	4	1.580	.....	.....	4.92	.....	Sky clear.	L. C.	2.08	.....
21 A. ...	4	1.486	1.514	1.373	4.40	.907	Sky clear.	L. C.	1.95	1.91
22 A. ...	4	1.497	.....	.....	3.90	.....	Sky 1.	L. C.	1.94	.....
23 A. ...	4	1.504	1.532	1.397	(3.38)?	.912	Sky 0, very clear.	L. C., H. P.	(1.93)?	1.90
24 A. ...	4	1.502	1.543	1.343	4.06	.870	Sky clear.	L. C.	1.96	1.95
28 A. ...	4	1.538	.....	.....	5.76	.....	Sky 1.	L. C.	2.05	.....
29 P. ...	4	1.454	1.472	1.352	4.54	.918	Sky 0, hazy near horizon.	H. P., L. C.	1.91	1.87
July 7 P. ...	2	1.445?	.....	.....	4.38	.....	Sky 2.	L. C.	1.89?	.....
8 A. & P.	6	1.505?	.....	.....	5.05	.....	Sky gen. clear, some haze.	L. C.	1.99?	.....
9 A. & P.	6	1.489	1.543	1.265	4.22	.820	Sky clear.	H. P.	1.94	1.98
10 A. ...	4	1.446	1.493	1.255	6.04	.813	Sky 2.	H. P., L. C.	1.94	1.97
11 A. ...	6	1.448	1.485	1.302	4.97	.877	Sky 3.	H. P.	1.92	1.90
13 A. ...	4	1.500	1.543	1.323	4.61	.858	Sky clear, but hazy.	L. C.	1.97	1.97
14 A. ...	4	1.532	1.590	1.310	4.25	.824	Sky clear.	L. C.	2.00	2.03
15 A. ...	4	1.499	1.547	1.305	4.02	.844	Sky 0, hazy.	H. P.	1.95	1.97
16 A	4	1.498	1.580	1.173	4.15	.....	Sky hazy, growing clearer.	L. C.	1.96	.....
17 A. ...	4	1.480	1.564	1.147	4.76	.....	Sky 1.	H. P.	1.95	.....
18 A. ...	4	1.443	1.471	1.335	5.55	.907	Sky clear.	L. C.	1.93	1.88
20 A. ...	4	1.549	1.555	1.527	2.33	.982	Sky clear.	L. C.	1.93	1.88
21 A. ...	4	1.521	1.585	1.264	2.87	.798	Sky hazy.	H. P.	1.93	2.00
22 A. ...	4	1.544	1.597	1.340	3.83	.839	Sky clear.	L. C.	2.00	2.02
23 A. ...	4	1.527	1.580	1.312	3.59	.830	Sky 3, windy.	H. P.	1.97	2.00
24 A. ...	4	1.550	1.600	1.347	3.49	.842	Sky 0.	L. C.	1.99	2.02
25 A. ...	4	1.556	1.590	1.423	2.85	.895	Sky 0.	H. P., L. C.	1.97	1.97
26 A. ...	4	1.544	1.635	1.180	2.70	.....	Sky hazy.	H. P.	1.94	.....
27 A. ...	2	1.543?	.....	.....	3.18	.....	Sky clear.	L. C.	1.97?	.....
28 A. ...	4	1.563	1.602	1.410	2.50	.880	Sky clear.	H. P.	1.96	1.98
29 A. ...	4	1.611	1.674	1.360	1.84	.812	Sky clear.	L. C.	1.96	2.08

TABLE I—*Arequipa Pyrheliometry* (Continued)

Date	No. of values read	Calories at air masses 1.2	1	2	Mean humidity mm.	Trans-mission coefficient a_2	Remarks	Observer	Solar constant Formula I	Formula II
July 31 A. ...	4	1.508	1.648	.....	3.13	.....	Sky 3.	H. P.	1.92	.....
Aug. 3 P. ...	2	1.488	.....	.....	3.79	.....	Sky 1.	H. P.	1.93	.....
4 A. ...	4	1.528	1.553	1.437	3.32	.925	Sky 0.	H. P.	1.95	1.92
5 A. ...	4	1.547	.....	.....	5.99	.....	Sky 0.	H. P., L. C.	2.06	.....
6 A. ...	4	1.528	.....	.....	3.48	.....	Sky 0, but hazy and windy.	H. P.	1.95	.....
7 A. ...	6	1.523	.....	.....	4.71	.....	Sky clear, 1.	L. C.	1.99	.....
8 A. ...	4	1.497	.....	.....	3.07	.....	Sky 1.	L. C.	1.90	.....
11 A. ...	4	1.504	.....	.....	4.13	.....	Sky 0.	H. P.	1.95	.....
12 A. ...	4	1.593	.....	.....	4.50	.....	Sky clear.	L. C.	2.08	.....
14 A. & P.	8	1.510	1.552	1.338	4.61	.862	Sky clear, hazy and windy.	H. P.	1.98	1.97
15 P. ...	4	1.514	1.550	1.387	4.24	.895	Sky clear, 1.	L. C.	1.96	1.93
18 P. ...	4	1.567	1.602	1.426	5.28	.890	Sky exceptionally clear.	L. C.	2.06	2.02
19 P. ...	4	1.540	1.585	1.360	3.51	.858	Sky very clear, windy.	L. C., H. P.	1.96	2.00
20 P. ...	4	1.530	1.569	1.375	3.49	.876	Sky clear.	H. P., L. C.	1.94	1.93
21 P. ...	4	1.479	1.499	1.397	3.67	.931	Sky 2-1, windy.	H. P., L. C.	1.88	1.83
22 P. ...	4	1.529	1.569	1.373	3.12	.875	Sky clear, windy.	L. C.	1.92	1.93
24 P. ...	2	1.494	.....	.....	4.49	.....	Sky 2.	L. C.	1.93	.....
25 P. ...	3	1.437	.....	.....	4.14	.....	Sky 2.	H. P.	1.84	.....
28 P. ...	4	1.508	1.541	1.370	5.39	.889	Sky 1.	L. C.	1.98	1.94
Sept. 2 P. ...	2	1.475	.....	.....	3.82	.....	Sky 2, windy.	H. P.	1.87	.....
7 P. ...	4	1.446	1.494	1.260	(4.00)?	.843	Sky 4.	L. C., H. P.	(1.84)?	1.86
8 P. ...	2	1.438	.....	.....	6.16	.....	Sky 2.	H. P.	1.90	.....
9 P. ...	2	.....	.....	.....	5.66	.....	Sky 5.	H. P.	.....	.....
11 P. ...	2	1.587?	.....	.....	4.77	.....	Sky 2, windy.	L. C.	2.04?	.....
12 P. ...	6	1.560	1.604	1.378	3.45	.859	Sky 0, windy.	L. C., H. P.	1.95	1.96
14 P. ...	2	.....	.....	.....	4.89	.....	Sky 2.	H. P.	.....	.....
15 P. ...	2	1.560	.....	.....	4.01	.....	Sky 2.	L. C.	1.97	.....

TABLE 1—*Arequipa Pyrheliometry* (Continued)

Date	No. of values read	Calories at air masses			Mean humidity mm.	Transmission coefficient a_2	Remarks	Observer	Solar constant	
		1.2	1	2					Formula I	Formula II
Sept. 16 P. ...	4	1.540	1.580	1.383	3.67	.875	Sky clear, windy.	H. P.	1.94	1.93
17 P. ...	4	1.548	1.594	1.368	3.98	.858	Sky 1.	L. C.	1.96	1.96
18 P. ...	4	1.488	1.519	1.366	(4.00)	.899	Sky 3, clear, windy.	H. P.	(1.89)	1.86
26 P. ...	4	1.531	1.580	1.337	4.65	.846	Sky 0-1.	L. C., H. P.	1.95	1.96
27 P. ...	4	1.544	1.591	1.360	5.69	.855	Sky clear, windy.	L. C., H. P.	2.00	1.99
28 P. ...	2	1.520	.....	.....	5.50	.....	Sky 3.	H. P.	1.96	.....
29 P. ...	4	1.538	1.582	1.364	5.54	.862	Sky clear, 1, windy.	L. C., H. P.	1.99	1.98
Oct. 4 P. ...	4	1.500	1.581	1.178	4.87	.....	Sky clear.	L. C., H. P.	1.92	.....
9 P. ...	4	1.523	1.592	1.251	5.02	.787	Sky 1.	L. C.	1.94	2.02
10 P. ...	4	1.470	1.500	1.349	4.83	.899	Sky clear.	L. C., H. P.	1.87	1.84
11 P. ...	2	1.500	.....	.....	4.75	.....	Sky clear, 1.	L. C.	1.91	.....
15 P. ...	4	1.573	1.615	1.400	5.21	.867	Sky clear.	L. C., H. P.	2.00	1.99
16 P. ...	4	1.566	1.609	1.370	4.61	.851	Sky clear.	H. P.	1.97	1.98
19 P. ...	2	1.557?	.....	.....	4.75	.....	Sky clear, windy.	L. C.	1.97?	.....
20 P. ...	4	1.563	1.616	1.349	5.19	.835	Sky clear.	L. C., H. P.	1.99	2.00
21 P. ...	2	1.543	.....	.....	5.45	.....	Sky 4, windy.	H. P.	1.97	.....
22 P. ...	4	1.511	1.565	1.302	5.24	.832	Sky clear, very windy.	L. C., H. P.	1.92	1.94
23 A. ...	6	1.590?	.....	.....	3.63	.....	Sky clear.	L. C.	1.97?	.....
24 A. ...	4	1.578	.....	.....	4.18	.....	Sky clear.	L. C., H. P.	1.97	.....
25 A. ...	4	1.562	.....	.....	4.18	.....	Sky clear.	L. C., H. P.	1.94	.....
26 A. ...	4	1.527	.....	.....	4.50	.....	Somewhat hazy.	L. C.	1.91	.....
27 A. ...	2	1.618	.....	.....	(4.50)	.....	Somewhat hazy.	L. C.	(2.03)	.....
28 P. ...	4	1.560	1.617	1.335	3.79	.826	Sky clear.	L. C.	1.93	1.96
29 P. ...	2	1.531	.....	.....	4.50	.....	Sky clear, windy.	L. C.	1.92	.....
30 A. ...	2	1.568	.....	.....	3.65	.....	Sky clear, windy.	L. C.	1.93	.....
31 A. ...	4	1.555	.....	.....	4.26	.....	Clear but hazy, windy.	L. C.	1.94	.....
Nov. 1 P. ...	4	1.507	1.574	1.234	4.95	.784	Sky clear, windy.	L. C.	1.90	1.96
3 P. ...	4	1.514	1.559	1.343	4.37	.861	Sky clear, windy.	L. C.	1.89	1.89
9 P. ...	2	1.564	.....	.....	(4.40)?	.....	Sky clear.	L. C.	(1.94)?	.....

TABLE 1—*Arequipa Pyrheliometry* (Continued)

Date	No. of values read	Calories at air masses			Mean humidity mm.	Trans-mission coefficient a_2	Remarks	Observer	Solar constant	
		1.2	1	2					Formula I	Formula II
Nov. 10 P. ...	4	1.549	1.596	1.363	5.31	.854	Sky clear.	L. C.	1.96	1.95
11 P. ...	2	1.550	.....	.....	4.81	.....	Sky 1, windy.	L. C.	1.94	.....
12 A. ...	4	1.555	.....	.....	4.50	.....	Sky clear.	L. C.	1.94	.....
24 P. ...	4	1.466	1.524	1.330	5.52	.873	Sky 1, windy.	H. P.	1.85	1.83
Dec. 7 P. ...	4	1.481	1.528	1.296	6.98	.848	Sky 4.	H. P.	1.89	1.89
12 A. & P.	6	1.547	1.592	1.364	6.64	.857	Sky 3-2.	H. P.	1.97	1.96
16 P. ...	2	1.544	.....	.....	5.80	.....	Sky 3.	H. P.	1.94	.....
17 P. ...	2	1.550	.....	.....	5.84	.....	Sky 3, windy.	H. P.	1.95	.....
19 A. ...	4	1.592	.....	.....	5.18	.....	Sky clear.	H. P., L. C.	1.99	.....
20 P. ...	2	1.594	.....	.....	4.50?	.....	Sky clear.	L. C.	1.97?	.....
24 A. ...	2	1.500	.....	.....	(5.50)?	.....	Sky 2.	L. C.	(1.88)?	.....
31 A. ...	2	1.543	.....	.....	6.65	.....	Sky clear.	L. C.	1.96	.....
1915										
Jan. 14 A. ...	4	1.535	.....	.....	6.47	.....	Sky 2.	L. C., H. P.	1.95	.....
15 A. ...	4	1.550	.....	.....	4.34	.....	Sky 2.	H. P.	1.90	.....
20 A. ...	4	1.485	.....	.....	4.76	.....	Sky 2.	L. C., H. P.	1.84	.....
Feb. 2 A. ...	4	1.475	.....	.....	8.98	.....	Sky 2.	L. C., H. P.	1.92	.....
9 A. ...	4	1.470	1.493	1.370	7.67	.917	Sky 3-5.	L. C., H. P.	1.90	1.85
10 A. ...	4	1.489	.....	.....	7.85	.....	Sky gen. clear, 3.	L. C., H. P.	1.93	.....
11 A. ...	4	1.478	.....	.....	9.49	.....	Sky 3-5.	H. P.	1.94	.....
Mar. 8 P. ...	4	1.526	1.554	1.411	(7.00)?	.908	Sky 1.	L. C., H. P.	(1.99)?	1.94
17 A. ...	4	1.430	1.465	1.297	8.52	.886	Sky 1.	L. C.	1.90	1.88
20 A. ...	6	1.480	1.520	1.328	7.29	.874	Sky 2.	L. C.	1.94	1.93
21 A. ...	4	1.460?	.....	.....	5.48	.....	Sky 1.	L. C.	1.88	.....
25 A. ...	6	1.518	1.560	1.353	(8.50)?	.867	Sky 1-0-0.	L. C.	(2.01)?	2.01
26 P. ...	4	1.517	.....	.....	9.55	.....	Sky clear.	L. C.	2.04	.....
27 P. ...	4	1.522	1.562	1.360	9.14	.870	Sky clear.	L. C.	2.04	2.04

TABLE 2—*Monthly Mean Values*

	Month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1912	Radiation .... $e_{1\cdot2}$	....	....	....	....	....	....	....	1.487	1.487	1.558	1.547	1.520
	Transmission .... a_2	....	....	....	....	....	....	....	.847	(.821)	.869	....	(.848)
	Vapor pressure .... p	....	....	....	....	....	....	....	....	....	....	3.00	7.28
*	Solar constant .... e_0	....	....	....	....	....	....	....	(1.93)	(1.91)	(1.98)	(1.97)	1.94
		....	....	....	....	....	....	....	....	....	....	....	1.97
	Number days .... n	....	....	....	....	....	....	....	13	25	21	7	8
1913	$e_{1\cdot2}$	1.469	(1.464)	(1.321)	1.412	1.478	1.501	1.470	1.457	1.478	1.425	1.503	1.518
	a_2	(.821)	....	(.845)	.851	.878	.879	.875	.856	.848	.826	(.843)	.831
	p	8.95	(9.65)	(8.00)	6.89	4.29	3.71	3.07	4.56	4.87	6.00	6.70	7.24
	e_0	1.91	....	....	1.86	1.92	1.94	1.87	1.88	1.90	1.86	1.92	1.93
		1.91	....	....	1.89	1.92	1.93	1.89	1.89	1.92	1.89	1.95	1.95
	n	5	1	1	6	12	15	17	19	18	13	12	15
1914	$e_{1\cdot2}$	1.495	1.463	1.470	1.485	1.451	1.496	1.514	1.516	1.521	1.542	1.529	1.544
	a_2	.838	(.861)	.886	.886	(.882)	.902	.855	.889	.862	.842	.843	....
	p	7.35	9.61	8.35	6.49	7.00	4.50	3.83	4.16	4.65	4.58	4.83	5.89
	e_0	1.91	1.91	1.93	1.95	1.94	1.96	1.95	1.96	1.94	1.95	1.92	1.94
		1.92	1.92	1.91	1.92	(1.90)	1.91	1.98	1.94	1.94	1.96	1.91	1.93
	n	11	11	15	14	6	11	22	18	13	19	7	8
1915	$e_{1\cdot2}$	1.523	1.478	1.493	....	....	....	....	....	....	....	....	....
	a_2	....	(.917)	.881	....	....	....	....	....	....	....	....	....
	p	5.19	8.50	7.93	....	....	....	....	....	....	....	....	....
	e_0	(1.90)	(1.92)	1.97	....	....	....	....	....	....	....	....	....
		....	(1.85)	1.96	....	....	....	....	....	....	....	....	....
	n	3	4	7	....	....	....	....	....	....	....	....	....
	Weighted mean $e_{1\cdot2}$	1.493	1.467	1.475	1.463	1.469	1.499	1.495	1.486	1.492	1.512	1.522	1.526
	values a_2	.832	(.880)	.878	.870	.880	.885	.865	.865	.850	.845	.843	.835
	all years p	7.42	9.58	8.28	6.60	5.20	4.05	3.48	4.36	4.77	5.15	6.00	6.80
	Total days .... n	19	16	23	20	18	26	39	50	56	53	26	28
	Weighted mean value for mean solar distance .... $e_{1\cdot2}$	1.448	1.434	1.462	1.474	1.502	1.547	1.543	1.521	1.511	1.500	1.488	1.480

* Computed by formulæ I and II as given below.

We now give in Table 2 mean monthly values of the intensity of solar radiation ($e_{1.2}$) at air mass 1.2, the transmission coefficient a_2, the pressure of aqueous vapor p, and the empirical solar constant values e_0, of which more is said below. The table gives also the number of days on which radiation was observed. This considerably exceeds the number of days on which the atmospheric transmission could be determined. Monthly means based on very meager data are indicated by parentheses.

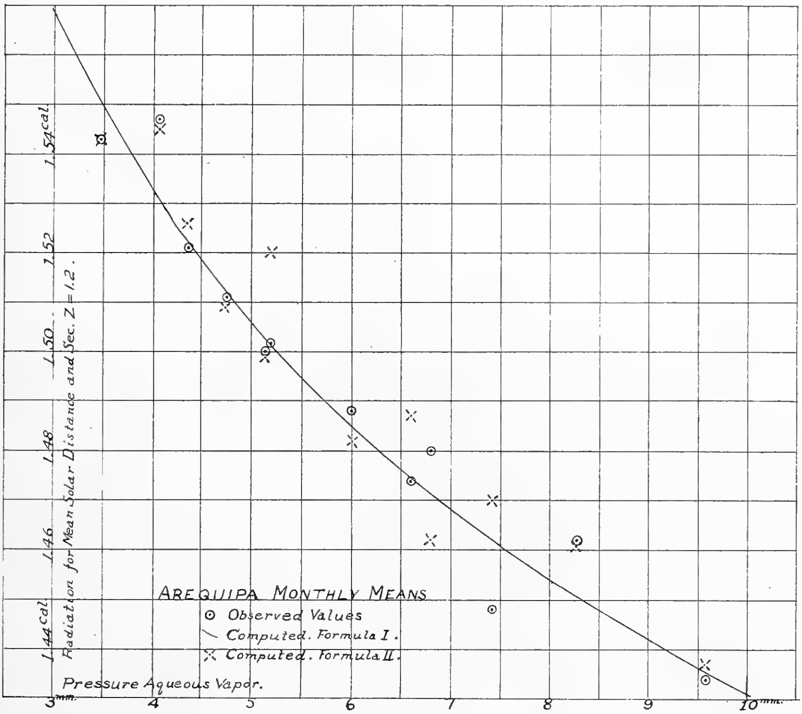

FIG. 1.

General mean: Of $e_{1.2} = 1.496$; of $a_2 = .860$; of $p = 5.97$.

Examination of the foregoing table fails to indicate any notable abnormalities covering considerable periods. In other words nothing appears to lead us to suppose that these were not normal years for Arequipa (unless as regards the *number* of clear days, on which we say nothing). This is especially interesting, for in the northern hemisphere the year 1912 was notable for the great decrease in direct solar radiation received at the earth's surface, and of atmospheric transparency, which speedily followed the volcanic eruption of Mt. Katmai in June of that year. Remnants of this volcanic

dust still remained distinguishable by pyrheliometry in the United States up to near the end of the year 1913. No indication of its presence above Arequipa in either 1912 or 1913 seems to be shown. The volcanic dust from Katmai, though general in the northern hemisphere, seems not to have crossed the equator.

In the last line of the table the mean monthly radiation values for the whole period of observation have been reduced to what they would have been if the sun's distance had remained uniform at its mean value. The close connection between solar radiation at the earth's surface, and atmospheric humidity is brought out graphically in fig. 1. Ordinates are mean monthly values of $e_{1.2}$ reduced to mean solar distance, abscissæ are corresponding mean monthly values of water vapor pressure (p). The smoothness of the curve defined by these points is remarkable. It is perhaps to be ascribed to the great altitude and inland location of Arequipa. Apparently the degree of atmospheric humidity at the earth's surface there is a good index of the total quantity of humidity existing between the station and the limit of the atmosphere.

It is obvious, of course, that fluctuations of atmospheric transmission coefficients must also produce their effects on the observed intensity of solar radiation at the station. Such fluctuations are of two kinds: First, those associated with changes of water vapor. Second, those associated with changes of dustiness, such as those produced in the northern hemisphere by the Katmai eruption. The influence on the solar radiation of fluctuations of the first type, which are a function of the humidity, may be generally (for a high-level station like Arequipa) much greater than those associated with dust alone. But it might well be expected that for certain months of the year the dust fluctuations would be by no means negligible. However, restricting our thought to a high-level station like Arequipa, and remembering the powerful true absorption produced in the infra-red spectrum by water vapor, and the large changes in this true absorption attending changes of humidity when the humidity and air mass are both small, it is easy to see after all why the observed radiation at $M=1.2$ at Arequipa seems to be so well represented as a function of water vapor alone. For both the true absorption and a large proportion of the variable elements of the general scattering are functions of water vapor. Compared to these, the variable scattering produced by dry dust alone is generally small.

In figure 2 the radiation, $e_{1.}$ (not reduced to mean solar distance), the vapor pressure, p, and the transmission, a_2, are all given as functions of the time of the year.

The data of figure I have been represented by the following two formulæ, one expressing the radiation $e_{1.2}$ (reduced to mean solar distance) as a function of vapor pressure, p, alone, the other as a function of vapor pressure, p, and transmission a_2:

Formula I. $e_{1.2}^{corr} = 0.981 + \frac{0.75}{p^{0.222}}$

Formula II. $e_{1.2}^{corr} = 1.50 + (5.25 - p)0.19 + (a_2 - 0.85)0.63$

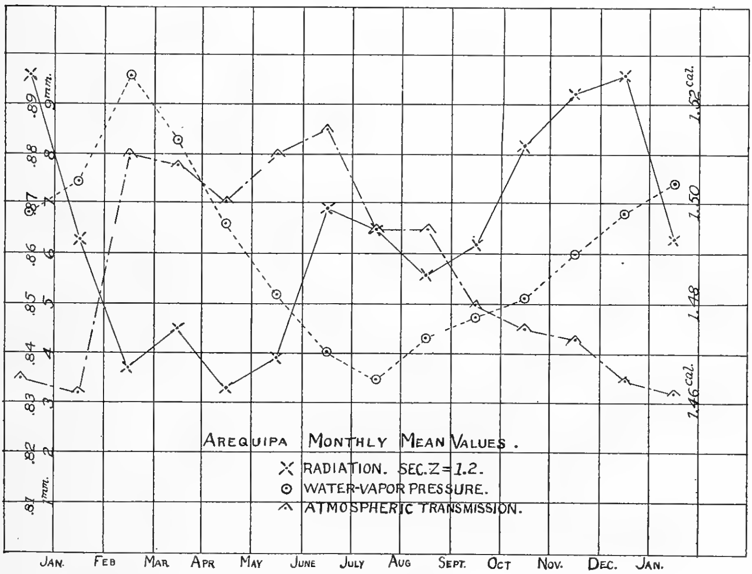

FIG. 2.

We now come to a very interesting application of these formulæ. During the period of about four years covered by the Arequipa observations, we may assign as the mean value of the solar constant of radiation outside the atmosphere 1.93 calories per sq. cm. per min. Dividing by this value we have the following empirical formulæ for obtaining from Arequipa daily observations values of the solar constant of radiation:

Formula I. $e_0 = \dfrac{e_{1.2}^{corr}}{0.508 + \dfrac{0.389}{p^{0.222}}}$.

Formula II. $e_0 = \dfrac{e_{1.2}^{corr}}{0.777 + (5.25 - p)0.01 + (a_2 - 0.85)0.33}$.

During the years 1913 and 1914 the solar constant was determined at Mount Wilson by spectro-bolometric observations on some of the days when these formulæ are applicable to Arequipa observations. From 34 comparisons of Arequipa and Mount Wilson solar constant values, the average deviation of individual days is about 2.5 per cent. Omitting 5 days when unusually great discrepancies occurred, owing to poor sky at one station or the other, the average deviation is only 2 per cent.

Under the circumstances it seemed unreasonable to hope that for individual days the empirically derived solar constant results from Arequipa observations would be of sufficient accuracy to show the short-period fluctuations of the solar constant. It might reasonably be expected, however, that monthly mean values would seldom differ by more than 1 per cent from the values obtained in corresponding months at Mount Wilson. Thus a new confirmation of the variability of the sun in its longer periods may be hoped for from pyrheliometry and psychrometry at Arequipa alone. This hope seems to be confirmed by the following Table 3. Both Arequipa values (formulæ I and II) are given, but the number of days relates to the first method values, which are more numerous.

TABLE 3—*Monthly Mean Solar Constant Values*

Month	1913 July	Aug.	Sept.	Oct.	Nov.	1914 June	July	Aug.	Sept.	Oct.
Arequipa	1.87	1.89	1.90	1.86	1.92	1.96	1.95	1.96	1.94	....
	1.89	1.89	1.92	1.89	....	1.91	1.98	1.94	1.94	....
No. days	17	18	18	11	12	11	22	18	13	....
Mount Wilson	1.925	1.931	1.920	1.874	1.876	1.952	1.956	1.964	1.943	....
No. days	3	18	25	24	5	14	14	22	18	....

The comparisons of July and November, 1913, have little weight because of the small number of days observed at Mount Wilson. Apart from these months only one, August, 1913, shows a difference of more than 1 per cent between Arequipa and Mount Wilson. Both stations agree in showing the interesting result that the solar constant was decidedly higher in 1914 than in 1913.

With the word of caution that individual day's values may often be in error by as much as 5 per cent, and on the average by as much as 2 per cent, we have included in Table 1 two columns giving the daily solar constant values determined from Arequipa pyrheliometry by means of formulæ I and II. Table 2 gives the mean monthly solar constant values by formulæ I and II. Months for which no values of vapor pressures are available are supplied by taking the

mean monthly vapor pressures for these months for several years as given in Table 2. Such solar constant values are given in parentheses.

Finally the 29 days with solar constant values available for favorable comparison between Mount Wilson and Arequipa have been divided into two groups of high and low values respectively, as indicated by Mount Wilson work. The mean values are as follows:

Station	Group I	No. days	Group II	No. days.	Group I–Group II
Mount Wilson	1.954	15	1.893	14	0.061
Arequipa { Formula I	1.936	15	1.900	14	0.036
Arequipa { Formula II	1.943	13	1.907	14	0.036

The days selected are these:

Group I. { 1913. Aug. 5, 12, 18; Sept. 2, 3, 9, 17, 18, 22.
1914. June 16, 23, 24; July 17, 23, 28.

Group II. { 1913. Aug. 4, 6, 15; Sept. 4, 8, 10, 26, 27, 29, 30; Oct. 1, 6, 31.
1914. June 21.

This comparison, so far as it has weight, evidently tends to confirm the existence of short-period irregular solar variations, discovered by other investigations.

SUMMARY.—Observations with the silver disk pyrheliometer and nearly simultaneous measurements of atmospheric humidity have been made since August, 1912, at Arequipa, Peru, at the station of the Harvard College Observatory.

From these observations have been determined values of the solar radiation at Arequipa corresponding with secant Z equal to 1.0, 1.2, and 2.0; values of pressure of aqueous vapor, and values of the diminution of radiation attending the passage of the sun from the zenith distance whose secant is 1.0 to that whose secant is 2.0.

Owing to other occupations the observers have generally made these observations when the sun was within 60° of the zenith. On this account determinations of atmospheric transparency are not always possible, and are of less weight than other data given.

The results are collected to give monthly mean values. These show a remarkably close connection between radiation and vapor pressure. Advantage is taken of this close correlation to determine by empirical formulæ values of the solar constant of radiation. These empirical values agree quite as well as could be expected with values obtained at Mount Wilson, California, by complete spectrobolometric and pyrheliometric measurements combined. The Are-

quipa results confirm the variability of the sun, both from year to year and from day to day, shown by investigations at Mount Wilson and elsewhere.

It seems probable that from observations similar to those at Arequipa, if conducted at eight or ten favorable stations of high level in various parts of the world, the variations of the sun could be determined almost or quite as certainly as from two stations equipped for complete spectro-bolometric determinations of the solar constant.

The Arequipa results indicate that the volcanic dust which was general in the atmosphere in the northern hemisphere for more than a year after the volcanic eruption of Mt. Katmai, Alaska, in June, 1912, did not influence the transparency of the atmosphere in Peru.

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A Phylogenetic Study of the Recent Crinoids, with Special Reference to the Question of Specialization Through the Partial or Complete Suppression of Structural Characters

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A PHYLOGENETIC STUDY OF THE RECENT CRINOIDS, WITH SPECIAL REFERENCE TO THE QUESTION OF SPECIALIZATION THROUGH THE PARTIAL OR COMPLETE SUPPRESSION OF STRUCTURAL CHARACTERS

By AUSTIN H. CLARK

CONTENTS

PREFACE

In the study of any group of animals from the systematic standpoint the ultimate aim is the arrangement of the units within the group in a sequence which shall conform as nearly as possible to their relative phylogenetic status.

The consummation of such an arrangement is not always an easy task, for we too commonly fall into the error of over-estimating the comparative value of, and thereby placing too much reliance upon, some single obvious or exaggerated character, instead of taking into consideration and carefully weighing all of the characters presented.

Thus we are prone to place types distinguished by some unique and phylogenetically aberrant feature, though not otherwise remarkable, ahead of others which, more conservative throughout, are except for this single feature more advanced.

The recent crinoids offer a good illustration of the many difficulties in the path of a logical phylogenetic arrangement. The sequence of the families now commonly accepted is, beginning with the most specialized, as follows:

Order Articulata

Pentacrinitidæ (including the Pentacrinitida and the Comatulida)
Apiocrinidæ
Phrynocrinidæ
Bourgueticrinidæ
Holopodidæ

Order Inadunata

Plicatocrinidæ

This sequence has been determined not by an exhaustive study of the characters of each type and a subsequent comparison based upon the results of such a study, but rather by a more or less fortunate application of the doctrine of probabilities, based upon general resemblances.

It is the aim of the present paper to analyze all of the characters employed in the differentiation of the larger groups of recent crinoids, and, on the basis of this analysis, to indicate the true linear phylogenetic interrelationships of the recent types.

THE DETERMINATION OF THE PHYLOGENETIC SIGNIFICANCE OF THE DIFFERENTIAL CHARACTERS EMPLOYED IN SYSTEMATIC WORK

In the systematic study of organisms the differential characters are always employed in pairs, the two components of each pair being contrasted with each other.

Within each group individual pairs have ordinarily only a limited application, serving for the differentiation of certain units, but being quite useless for the differentiation of others.

Thus in every large group a large number of such contrasted pairs of characters must be employed, each of them having a more or less limited value.

A detailed study of the pairs of contrasted characters used in the differentiation of the groups of recent crinoids, and especially of the relation of the two components of each pair to each other, should not only indicate the phylogenetic interrelationships of the various types, but should also show clearly by what broad principle phylogenetic advance, or specialization, has come about.

Therefore in addition to determining the correct phylogenetic status of each of the groups of recent crinoids, an attempt will be made in the present paper to analyze the pairs of contrasted characters in an effort to discover the significance of each of the components, and thereby to indicate along what lines the phylogenetic development of the crinoids has progressed.

THE COURSE TAKEN BY PHYLOGENETIC PROGRESS, OR PROGRESSIVE SPECIALIZATION, AMONG THE CRINOIDS

The dominant feature of the progressive specialization among the crinoids from the earliest times to the present day has always been a process of progressive simplification in structure, the result of a process of progressive atrophy or suppression affecting some part or other of the organism. Thus the more specialized types differ from the more generalized through the atrophy or suppression of some important structural element, while the later groups are differentiated among themselves according to the lines which this atrophy or suppression has followed.

In a broad way this has long been appreciated; we recognize that the (recent) Articulata are distinguished from the Inadunata by the extreme atrophy of their calyx, involving in most cases the complete disappearance of certain essential elements; the comatulids are differentiated from all other (recent) types by the suppression of the column, excepting only the topmost columnal which becomes permanently attached to the calyx; *Holopus* is differentiated from all other (recent) genera through the suppression of the column excepting only the base, upon which directly the calyx rests; the Phrynocrinidæ differ from the Bourgueticrinidæ in the complete suppression of the radicular cirri; and the Bourgueticrinidæ differ from the Phrynocrinidæ in the suppression of the terminal stem plate. But as yet no attempt has been made to apply this principle to all of the differential characters which collectively make up the crinoid whole.

THE APPARENTLY NEW STRUCTURES IN THE LATER CRINOIDS

In the process of development and specialization of the crinoid phylogenetic line no new features have been added; nothing is found in the later and more specialized types that does not occur, usually in a more extended form, in the earlier and more generalized.

There are two apparent exceptions to this statement. The pentacrinites and the comatulids are chiefly remarkable for the great development of cirri, which are unknown in most of the earlier types and which therefore might be assumed to be of relatively recent phylogenetic origin; and most of the later forms possess one or more series of paired plates, of which the outermost is axillary, interpolated between the radials and the arm bases, whereas in the more primitive types the arms are given off directly from the radials.

As is explained further on, in the Articulata the column, after reaching a certain definite length, abruptly ceases further development, and the last formed columnal becomes permanently attached to the calyx. Though the skeletal development of the column ceases abruptly, the growth of the other constituents of the column is not so suddenly arrested, for we notice that the columnal which is attached to the calyx increases in size and gradually becomes more or less differentiated from the other columnals. If the column be very short—in other words if the suppression of the columnar development has been very abrupt—cirri are developed which break through the walls of the enlarged topmost columnal. These cirri, invariably associated with atrophied, dwarfed, or attenuated columns, represent a diffuse lateral diversion of the normally linear longitudinal stem development. The sudden suppression of the development of the skeleton of the column is not correlated with a correspondingly sudden suppression in the development of the other systems which enter into the columnar structure; and the organic adjustment or equilibrium necessitated by the continued development of the organic portions of the column after the inorganic portion has reached its limit is attained by a lateral diversion of this ontogenetic force, resulting in the formation of a varying number of cirri, each of the cirri representing a fractional degenerate derivative from a suppressed column of the normal type, while all of the cirri collectively represent the degree of excess of development possessed by the "soft parts" of the column over that possessed by the skeleton.

In order to understand the significance of the pair of ossicles in the later ten-armed types which occur between the radials and the arm bases it is necessary to bear in mind that the radials are not true

calyx plates, but arm plates. The true calyx plates are (1) the basals, corresponding to the genitals in the urchins, and (2) the infrabasals, corresponding to the echinoid oculars. The radials, which always retain traces of an ultimate origin from two fused plates, are in practically all types the basic plates of the arms; but possibly they were originally the second arm plates, for in many of the older types there occur beneath one or more of them, most commonly under the right posterior, small additional plates which separate them from the infrabasals. This small plate beneath the right posterior radial is known as the radianal; in the young comatulid the same plate, which usually appears at a greater or lesser distance from its original position, has almost universally been designated as the anal, though it does not correspond to the anal of the older types.

As the calyx, through specialization by atrophy, decreases in size, the arms which, being composed dorsally of an extension of the heavily calcified dorso-lateral wall of the calyx and ventrally of an extension of the ventral surface of the disk which draws out along these skeletal supports prolongations from the various ring systems about the mouth, are necessarily situated where these two divisions of the body surface join, cannot accompany the radials in their distalward migration. The increasing gap between the radials and the arm bases is therefore filled by a pair of apparently new plates of which the outer, almost invariably axillary, is a double plate, a very close duplication of the radials, but with the two original elements less completely fused, while that between it and the original radial possibly represents the original subradial. The forms with the division series composed of paired ossicles (such as the species of *Endoxocrinus* for example) thus possess between the radials and the arm bases a series of paired plates, the inner plate of each pair resting upon the radial itself, or upon the outer plate of a preceding pair, and the outer plate of each pair being a reduplication of the original radial. Thus these paired plates of which the division series are formed in most of the later crinoids are not in any way new structures, but an adaptation through a system of reduplication, involving a complicated twinning process, of plates of fundamental significance common to all crinoids. The formation of the division series of paired plates is exactly comparable to the formation of the column in the pentacrinites, which involves a continuous linear repetition of the complete original column, each unit corresponding to the original column resting upon a cirriferous nodal as a terminal stem plate, and terminating itself in a cirriferous nodal, which, though in origin

and significance a true proximale, never succeeds in attaching itself permanently to the calyx.

Thus upon close analysis neither the cirri nor the paired division series are found to be in reality new structures; the cirri, which occur sporadically in certain of the older types as well as uniformly in many of the later, are always associated with atrophy, dwarfing or attenuation of the column, and are in reality merely the evidence of the diversion of the column-forming substance from its original intent in the direction of the production of imperfect fractional columns, while the paired division series are merely reduplications of the primitive arm base, made necessary by the atrophy of the calyx and the consequent creation of a gap between the radials, of necessity in contact with the true calyx plates, and the arm bases, of necessity situated on the border between the ventral and the lateral surfaces of the animal.

THE CONTRASTING CHARACTERS USED IN DIFFERENTIATING THE GROUPS OF RECENT CRINOIDS, WITH THE FAMILIES EXHIBITING EACH, AND AN EXPLANATION OF THEIR DIFFERENTIAL AND PHYLOGENETIC SIGNIFICANCE

In the following pages, grouped under the headings "I. Calyx, II. Column, III. Disk, IV. Arms, V. Pinnules and VI. General," are listed all of the more important differential characters of broader significance found in the recent crinoids.

These characters are given in contrasting pairs, the more generalized being in each case numbered "1" and the more specialized numbered "2."

In each of these pairs the more specialized character (2) is always derived from the more generalized by a process of degeneration through reduction or more or less complete suppression.

Under each member of each pair are grouped the families presenting the character as described with its bathymetric and thermal distribution, and after each pair the significance of the two contrasting characters is pointed out, as well as the significance of the difference between them.

I. CALYX

1. Calyx in the form of a cup, protecting the viscera dorsally and laterally.

	Bathymetric range	Thermal range
Holopodidæ	5–120	71.0
Plicatocrinidæ	266–2575	31.1–43.9

2. Calyx forming a platform upon which the viscera rest, more or less supported by the arm bases.

	Bathymetric range	Thermal range
Pentacrinitidæ	0–2900	28.7–80.0
Apiocrinidæ	565–940	36.7–38.1
Phrynocrinidæ	508–703	38.1–40.0
Bourgueticrinidæ	62–2690	29.1–70.75

In the majority of the older crinoids, as well as in the pentacrinoid young of the comatulids, the visceral mass is protected dorsally and laterally by two or three alternating rings of plates, with the summit of the column covering the opening in the center of the innermost ring.

In the later types, as in the developing young of the comatulids, we see a progressive decrease in the relative size of the calyx plates, as a result of which they become more and more restricted to the dorsal apex, leaving more and more of the lateral portion of the visceral mass exposed, until finally they become so reduced as to serve merely as a platform upon which the dorsal apex of the visceral mass rests, the lateral portions being supported by the arm bases.

The reduction of the crinoid calyx from the primitive condition of a cup entirely enclosing and protecting laterally and dorsally the visceral mass, is obviously specialization by inhibition and progressive suppression of the skeleton forming power; it is correlated with a similar reduction affecting other portions of the skeleton.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	1	2	80–75	0	1
100–200	1	2	75–70	1	2
200–300	1	2	70–65	0	2
300–400	1	2	65–60	0	2
400–500	1	2	60–55	0	2
500–600	1	4	55–50	0	2
600–700	1	4	50–45	0	2
700–800	1	4	45–40	1	2
800–900	1	3	40–35	1	4
900–1000	1	3	35–30	1	2
1000–1500	1	2	30–25	0	2
1500–2000	1	2			
2000–3000	1	2			

	1	2
Average depth	808 fathoms	785 fathoms
Average temperature	$\left\{\begin{matrix}71.0^\circ\\37.5^\circ\end{matrix}\right\}$ Fahr.	50.1° Fahr.

1. Calyx reduced by the moving inward of all the calyx plates, so that they become closely appressed and, their longitudinal axes all being parallel, form a closely knit column upon the summit of which the visceral mass rests.

	Bathymetric range	Thermal range
Phrynocrinidæ (*Naumachocrinus*)	508–703	38.1–40.0
Bourgueticrinidæ	62–2690	29.1–70.75

2. Calyx reduced by the eversion and imbrication of the calyx plates, so that eventually they come to form a platform composed of superposed circlets of plates, all the plates in the same circlet lying in the same plane.

	Bathymetric range	Thermal range
Pentacrinitidæ	0–2900	28.7–80.0
Apiocrinidæ	565–940	36.7–38.1
Phrynocrinidæ (*Phrynocrinus*)...	508–703	38.1–40.0

One type of calyx reduction consists in the calyx abruptly ceasing growth upon reaching its perfected form, or, in the most extreme cases, closing up after the manner of an umbrella, so that the visceral mass, which continues to grow, is extruded and thus comes to lie, entirely exposed laterally, upon the summit of a short column composed of the much narrowed and more or less aligned calyx plates, supported chiefly by the arm bases.

But more commonly the reduction of the calyx plates takes the course of a progressive retardation in their development whereby they become smaller and smaller in relation to the lateral and dorsal area of the visceral mass, the inner edges of the plates of each circlet, as the circlets decrease in diameter, slipping inward over the outer edges of the plates of the circlet next within.

These two types of calyx reduction are, in a way, parallel to each other; yet the first appears to be of a more primitive character than the second, for the reason that the cessation of calyx growth and development does not begin until after the calyx has reached its perfected form, whereas in reduction by the second method the alteration of the relation of the calyx plates begins, at least in the developing comatulids, in the very early stages before the elimination of the radianal from the radial circlet. Thus it would appear logical to derive the second type from the first by carrying the inhibition of the formation of the calyx further back in the ontogeny or in the phylogeny.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	1	1	80–75	0	1
100–200	1	1	75–70	1	1
200–300	1	1	70–65	1	1
300–400	1	1	65–60	1	1
400–500	1	1	60–55	1	1
500–600	2	3	55–50	1	1
600–700	2	3	50–45	1	1
700–800	2	3	45–40	1	1
800–900	1	2	40–35	2	3
900–1000	1	2	35–30	1	1
1000–1500	1	1	30–25	1	1
1500–2000	1	1			
2000–3000	1	1			

	1	2
Average depth	777 fathoms	771 fathoms
Average temperature	48.8° Fahr.	50.2° Fahr.

1. Basals present.

	Bathymetric range	Thermal range
Pentacrinitidæ (Atelecrinidæ; Pentacrinitida)	5–1350	36.0–71.0
Apiocrinidæ	565–940	36.7–38.1
Phrynocrinidæ	508–703	38.1–40.0
Bourgueticrinidæ	62–2690	29.1–70.75
Plicatocrinidæ	266–2575	31.1–43.9

2. No basals.

	Bathymetric range	Thermal range
Pentacrinitidæ (Comatulida, except Atelecrinidæ)	0–2900	28.7–80.0
Holopodidæ	5–120	71.0

In the crinoids, including the developing comatulids, the two sets of plates which appear to be of the greatest importance are the basals and the radials, the former true calyx plates (corresponding to the echinoid genitals) and the latter properly speaking arm plates, though always forming part of the calyx cup.

It is only in types of very late occurrence, and, among the comatulids, very late in the ontogeny, that the basals become atrophied and disappear.

The elimination of the basals from the calyx in the more perfected types indicates phylogenetic advance through suppression of one of the most fundamental crinoid structures.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	2	2	80–75	0	1
100–200	2	2	75–70	2	2
200–300	3	1	70–65	2	1
300–400	3	1	65–60	2	1
400–500	3	1	60–55	2	1
500–600	5	1	55–50	2	1
600–700	5	1	50–45	2	1
700–800	5	1	45–40	3	1
800–900	4	1	40–35	5	1
900–1000	4	1	35–30	2	1
1000–1500	3	1	30–25	1	1
1500–2000	2	1			
2000–3000	2	1			

	1	2
Average depth	761 fathoms	713 fathoms
Average temperature	49.0° Fahr.	54.1° Fahr.

1. Five basals.

	Bathymetric range	Thermal range
Pentacrinitidæ	5–1350	36.0–71.0
Apiocrinidæ	565–940	36.7–38.1
Phrynocrinidæ	508–703	38.1–40.0
Bourgueticrinidæ	62–2690	29.1–70.75
Plicatocrinidæ (*Calamocrinus*)	392–782	38.5–43.9

2. Less than five basals.

	Bathymetric range	Thermal range
Plicatocrinidæ (except *Calamocrinus*)	266–2575	31.1–43.9

The number of the basals in the crinoids, like the number of the corresponding plates, the genitals, in the urchins, appears fundamentally to be five.

Variation from this number, which is always by reduction, appears invariably to be an indication of specialization, for it always occurs in correlation with specialization in other directions.

The reduction in the number of basals from five to three is an example of specialization through suppression; though the reduction is by coalescence and not by loss of two of the original five, and therefore all of the original substance included in the primitive five basals is equally included in the specialized three, the segregation of four into two pairs indicates a suppression of the individuality of the units involved, though without an actual loss of their substance.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	2	0	80–75	0	0
100–200	2	0	75–70	2	0
200–300	2	1	70–65	2	0
300–400	3	1	65–60	2	0
400–500	3	1	60–55	2	0
500–600	5	1	55–50	2	0
600–700	5	1	50–45	2	0
700–800	5	1	45–40	3	1
800–900	3	1	40–35	5	1
900–1000	3	1	35–30	1	0
1000–1500	2	1	30–25	1	0
1500–2000	1	1			
2000–3000	1	1			

	1	2
Average depth	681 fathoms	936 fathoms
Average temperature	49.8° Fahr.	40.0° Fahr.

1. Basals separate.

	Bathymetric range	Thermal range
Pentacrinitidæ (*Atelecrinus;* Pentacrinitida)	5–1350	36.0–71.0
Apiocrinidæ	565–940	36.7–38.1
Phrynocrinidæ	508–703	38.1–40.0
Bourgueticrinidæ (*Monachocrinus, Democrinus, Bythocrinus*)	62–2217	37.4–40.5
Plicatocrinidæ (*Calamocrinus, Hyocrinus, Gephyrocrinus, Thalassocrinus*)	392–2575	31.1–43.9

2. Basals fused into a single calcareous element.

	Bathymetric range	Thermal range
Pentacrinitidæ (except *Atelecrinus* and Pentacrinitida)	0–2900	28.7–80.0
Bourgueticrinidæ (*Ilycrinus, Bathycrinus, Rhizocrinus*)	77–2535	30.9–48.7
Plicatocrinidæ (*Ptilocrinus*)	266–2485	35.3

Primarily the basals form each a separate and distinct skeletal element at the head of one of the interradial areas.

But, if through reduction of the calyx in its relation to the visceral mass, or in any other way, the basals lose their intimate connection with the structures lying immediately within them, they also lose more or less their individuality, becoming closely united and forming a single skeletal element, a ring or "rosette," which in extreme cases is functionally little more than a topmost columnal, for which, indeed, it has often been mistaken.

The reduction of the basals and their fusion into a single calcareous element is evidence of the inhibition and suppression of the normal skeleton forming power by which the basal ring primarily develops from five distinct centers in the form of a circlet of five similar large, separate and perfect plates.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	2	2	80–75	0	1
100–200	2	2	75–70	1	1
200–300	2	3	70–65	1	1
300–400	3	3	65–60	1	1
400–500	3	3	60–55	1	1
500–600	5	3	55–50	1	1
600–700	5	3	50–45	1	2
700–800	5	3	45–40	3	2
800–900	4	3	40–35	5	3
900–1000	4	3	35–30	1	2
1000–1500	3	3	30–25	0	1
1500–2000	2	3			
2000–3000	2	3			

	1	2
Average depth	774 fathoms	846 fathoms
Average temperature	47.1° Fahr.	48.4° Fahr.

1. Infrabasals present as individual plates.

	Bathymetric range	Thermal range
Pentacrinitidæ (*Teliocrinus, Hypalocrinus, Metacrinus, Isocrinus*)	5–1350	36.0–71.0

2. Infrabasals absent, or fused with other plates.

	Bathymetric range	Thermal range
Pentacrinitidæ (Comatulida, and *Endoxocrinus*)	0–2900	28.7–80.0
Bourgueticrinidæ	62–2690	29.1–70.75
Holopodidæ	5–120	71.0
Plicatocrinidæ	266–2575	31.1–43.9

The infrabasals, which correspond to the oculars of the echinoids, do not appear to be of such fundamental significance as their representatives in that group, for in the earlier crinoids they may or may not be present. But whatever their status in the ancient types may be, they are regarded as either actually or potentially present in the order Articulata, to which all but one of the recent families belong.

Primarily the infrabasals occur as five small plates within (or below) the basal ring, and alternating in position with the basals.

Although potentially present in all the recent families of the Articulata, at best the infrabasals are represented by insignificant plates, invisible exteriorly, in the adults, while usually they are represented only in the very young, or are absent altogether.

The progressive suppression and final elimination of the infrabasals, plates which, so far as we know, are of fundamental importance in the Articulata, is directly correlated with the specialization of the respective types. The Plicatocrinidæ, which belong not to the Articulata but to the Inadunata, represents probably a primarily monocyclic type.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	1	3	80–75	0	1
100–200	1	3	75–70	1	3
200–300	1	3	70–65	1	2
300–400	1	3	65–60	1	2
400–500	1	3	60–55	1	2
500–600	1	3	55–50	1	2
600–700	1	3	50–45	1	2
700–800	1	3	45–40	1	3
800–900	1	3	40–35	1	3
900–1000	1	3	35–30	0	3
1000–1500	1	3	30–25	0	2
1500–2000	0	3			
2000–3000	0	3			

	1	2
Average depth	568 fathoms	808 fathoms
Average temperature	58.0° Fahr.	50.5° Fahr.

1. Five radials.

	Bathymetric range	Thermal range
Pentacrinitidæ (except *Promachocrinus* and *Thaumatocrinus*)	0–2900	28.7–80.0
Apiocrinidæ	565–940	36.7–38.1
Phrynocrinidæ	508–703	38.1–40.0
Bourgueticrinidæ	62–2690	29.1–70.75
Holopodidæ	5–120	71.0
Plicatocrinidæ	266–2575	31.1–43.9

2. Ten radials.

	Bathymetric range	Thermal range
Promachocrinus	10–222	28.7
Thaumatocrinus	361–1800	37.4–42.7

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	2	1	80–75	1	0
100–200	2	1	75–70	3	0
200–300	3	1	70–65	2	0
300–400	3	1	65–60	2	0
400–500	3	1	60–55	2	0
500–600	5	1	55–50	2	0
600–700	5	1	50–45	2	0
700–800	5	1	45–40	3	1
800–900	4	1	40–35	5	1
900–1000	4	1	35–30	3	0
1000–1500	3	1	30–25	2	1
1500–2000	3	1			
2000–3000	3	0			

	1	2
Average depth	822 fathoms	666 fathoms
Average temperature	49.5° Fahr.	35.8° Fahr.

1. Interradials present.

	Bathymetric range	Thermal range
Promachocrinus	10–222	28.7
Thaumatocrinus	361–1800	37.4–42.7

2. Interradials absent.

	Bathymetric range	Thermal range
Pentacrinitidæ (except *Promachocrinus* and *Thaumatocrinus*)	0–2900	28.7–80.0
Apiocrinidæ	565–940	36.7–38.1
Phrynocrinidæ	508–703	38.1–40.0
Bourgueticrinidæ	62–2690	29.1–70.75
Holopodidæ	5–120	71.0
Plicatocrinidæ	266–2575	31.1–43.9

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	1	2	80–75	0	1
100–200	1	2	75–70	0	3
200–300	1	3	70–65	0	2
300–400	1	3	65–60	0	2
400–500	1	3	60–55	0	2
500–600	1	5	55–50	0	2
600–700	1	5	50–45	0	2
700–800	1	5	45–40	1	3
800–900	1	4	40–35	1	5
900–1000	1	4	35–30	0	3
1000–1500	1	3	30–25	1	2
1500–2000	1	3			
2000–3000	0	3			

	1	2
Average depth	666 fathoms	822 fathoms
Average temperature	35.8° Fahr.	49.5° Fahr.

1. Anal *x*, bearing a process, present.

	Bathymetric range	Thermal range
Promachocrinus	10–222	28.7
Thaumatocrinus	361–1800	37.4–42.7

2. Anal *x* absent.

	Bathymetric range	Thermal range
Pentacrinitidæ (except *Promachocrinus* and *Thaumatocrinus*)....	0–2900	28.7–80.0
Apiocrinidæ	565–940	36.7–38.1
Phrynocrinidæ	508–703	38.1–40.0
Bourgueticrinidæ	62–2690	29.1–70.75
Holopodidæ	5–120	71.0
Plicatocrinidæ	266–2575	31.1–43.9

The problem of the so-called interradials in *Promachocrinus* and *Thaumatocrinus* is a very complicated one.

These five interradial radials arise as five simple interradials, corresponding exactly to the interradials of many fossil forms, and that in the posterior interradius gives rise to a process, being the homologue of the anal *x* of fossil types.

These interradial radials being primarily interradials, and the one in the posterior interradius being the representative of anal *x*, it naturally follows that the forms in which they occur present a more primitive type of structure, more nearly similar to the ancient structural types, than those from which they are absent as a result of the progressive simplification of the skeleton by the gradual suppression and elimination of superfluous calcareous elements.

But on the other hand these interradial radials do not retain the status of simple interradials. They grow to an equal size with the true radials, and each gives rise to a post-radial process which, starting as a simple linear series of ossicles, eventually comes to be exactly like that arising from the true radials.

This type of structure is quite unique, and may therefore be considered as an evidence of specialization.

Hence the five interradial radials of *Promachocrinus* and *Thaumatocrinus* must be considered, if viewed in the light of their origin, as indicating a low degree of specialization marked by the retention of the primitive interradials, and of anal *x;* but if viewed in the light of their ultimate condition, as indicating a high degree of specialization.

It may be remarked that in certain fossil types there are analogous cases of doubling of the radials through a transformation into radials of plates originally of quite different significance.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	1	2	80–75	0	1
100–200	1	2	75–70	0	3
200–300	1	3	70–65	0	2
300–400	1	3	65–60	0	2
400–500	1	3	60–55	0	2
500–600	1	5	55–50	0	2
600–700	1	5	50–45	0	2
700–800	1	5	45–40	1	3
800–900	1	4	40–35	1	5
900–1000	1	4	35–30	0	3
1000–1500	1	3	30–25	1	2
1500–2000	1	3			
2000–3000	0	3			

	1	2
Average depth	666 fathoms	822 fathoms
Average temperature	35.8° Fahr.	49.5° Fahr.

1. Interbrachials present.

	Bathymetric range	Thermal range
Pentacrinitidæ (Comasterinæ, Calometridæ, *Mastigometra*, *Antedon*, *Erythrometra*, Pentacrinitida)	0–1350	36.0–80.0
Plicatocrinidæ	266–2575	31.1–43.9

2. Interbrachials absent.

	Bathymetric range	Thermal range
Pentacrinitidæ (except Comasterinæ, Calometridæ, *Mastigometra*, *Antedon*, *Erythrometra*, Pentacrinitida)	0–2900	28.7–80.0
Apiocrinidæ	565–940	26.7–38.1
Phrynocrinidæ	508–703	38.1–40.0
Bourgueticrinidæ	62–2690	29.1–70.75
Holopodidæ	5–120	71.0

Interbrachials, characteristic of most fossil crinoids, occur, usually as small and thin, more or less irregular and poorly developed, plates, in many recent types.

Usually, however, they are quite absent, at least in adults.

The disappearance of the interbrachials is quite in line with the progressive development of the crinoid skeleton through the progressive elimination of the less essential elements.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	1	3	80–75	1	1
100–200	1	3	75–70	1	3
200–300	2	2	70–65	1	2
300–400	2	2	65–60	1	2
400–500	2	2	60–55	1	2
500–600	2	4	55–50	1	2
600–700	2	4	50–45	1	2
700–800	2	4	45–40	2	2
800–900	2	3	40–35	2	4
900–1000	2	3	35–30	1	2
1000–1500	2	2	30–25	0	2
1500–2000	1	2			
2000–3000	1	2			

	1	2
Average depth	750 fathoms	747 fathoms
Average temperature	52.5° Fahr.	51.0° Fahr.

II. COLUMN

1. Entire column present.

	Bathymetric range	Thermal range
Apiocrinidæ	565–940	36.7–38.1
Phrynocrinidæ	508–703	38.1–40.0
Bourgueticrinidæ	62–2690	29.1–70.75
Holopodidæ	5–120	71.0
Plicatocrinidæ	266–2575	31.1–43.9

2. Original column discarded in early life.

	Bathymetric range	Thermal range
Pentacrinidæ	0–2900	28.7–80.0

Whatever may be said of crinoids as a whole, or of echinoderms as a class, the column is an essential feature of the structure of the Articulata, to which all of the recent crinoids except those of the family Plicatocrinidæ belong, and of the Inadunata, which includes that family.

The absence of the column, or the atrophy and rejection of the larval stem, therefore, is clear evidence of specialization.

The rejection of the column in the young and the subsequent adoption of a so-called free existence, is an example of specialization through the suppression of an originally fundamental structure.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	2	1	80–75	0	1
100-200	2	1	75–70	2	1
200–300	2	1	70–65	1	1
300–400	2	1	65–60	1	1
400–500	2	1	60–55	1	1
500–600	4	1	55–50	1	1
600–700	4	1	50–45	1	1
700–800	4	1	45–40	2	1
800–900	3	1	40–35	4	1
900–1000	3	1	35–30	2	1
1000–1500	2	1	30–25	1	1
1500–2000	2	1			
2000–3000	2	1			

	1	2
Average depth	785 fathoms	808 fathoms
Average temperature	47.5° Fahr.	52.5° Fahr.

1. Column jointed.

	Bathymetric range	Thermal range
Apiocrinidæ	565–940	36.7–38.1
Phrynocrinidæ	508–703	38.1–40.0
Bourgueticrinidæ	62–2690	29.1–70.75
Plicatocrinidæ	266–2575	31.1–43.9

2. Column unjointed.

	Bathymetric range	Thermal range
Holopodidæ	5–120	71.0

Not only are the Articulata and the Inadunata fundamentally provided with a column, but that column is primarily composed of numerous short ossicles united end to end in the form of a long jointed stem.

The reduction of this jointed column to a simple calcareous base is therefore a form of specialization over the original condition, as is evident from a study of the earlier types, and from a study of the developing young.

The reduction of the primitive long jointed column to a single spreading base is evidently an example of specialization through suppression of the normal stem forming power.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	1	1	80–75	0	0
100–200	1	1	75–70	1	1
200–300	2	0	70–65	1	0
300–400	2	0	65–60	1	0
400–500	2	0	60–55	1	0
500–600	4	0	55–50	1	0
600–700	4	0	50–45	1	0
700–800	4	0	45–40	2	0
800–900	3	0	40–35	4	0
900–1000	3	0	35–30	2	0
1000–1500	2	0	30–25	1	0
1500–2000	2	0			
2000–3000	2	0			

	1	2
Average depth	828 fathoms	60 fathoms
Average temperature	45.8° Fahr.	71.0° Fahr.

1. Column composed of short cylindrical ossicles bearing radial crenellæ on their articular faces.

	Bathymetric range	Thermal range
Plicatocrinidæ	266–2575	31.1–43.9

2. Column not composed of short cylindrical ossicles bearing radial crenellæ on their articular faces.

	Bathymetric range	Thermal range
(Pentacrinitidæ)	0–2900	28.7–80.0
Apiocrinidæ	565–940	36.7–38.1
Phrynocrinidæ	508–703	38.1–40.0
Bourgueticrinidæ	62–2690	29.1–70.75
Holopodidæ	5–120	71.0

In all primitive types, and in practically all of the Palæozoic crinoids, the column is composed of a great number of short cylindrical ossicles with their circular articular faces marked with radial crenellæ.

But in most of the families of the Articulata, and in a few of the earlier forms, such for instance as the Platycrinidæ, the column, in addition to a marked decrease in the number of the columnals, has been greatly reduced in volume through the reduction in size of each of the component ossicles which, instead of being circular in cross section, have become elliptical, the long axes of the ellipses representing the diameter of the original circle, and the difference in length between the two axes indicating the amount of calcareous matter lost; rigidity is maintained in this (the so-called "bourgueti-

crinoid ") type of column by a difference in the direction of the long axes of the ellipses at either end of each columnal whereby the column as a whole forms a series of spirals.

The bourgueticrinoid type of column, with its relatively few columnals, each of the minimum volume compatible with the necessary rigidity, is a good instance of specialization through the gradual suppression of the skeleton forming power of the animal.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	0	3	80–75	0	1
100–200	0	3	75–70	0	3
200–300	1	2	70–65	0	2
300–400	1	2	65–60	0	2
400–500	1	2	60–55	0	2
500–600	1	4	55–50	0	2
600–700	1	4	50–45	0	2
700–800	1	4	45–40	1	2
800–900	1	3	40–35	1	4
900–1000	1	3	35–30	1	2
1000–1500	1	2	30–25	0	2
1500–2000	1	2			
2000–3000	1	2			

	1	2
Average depth	936 fathoms	747 fathoms
Average temperature	37.5° Fahr.	51.0° Fahr.

1. Column composed of a single type of columnals, without a proximale or nodals.

	Bathymetric range	Thermal range
Plicatocrinidæ	266–2575	31.1–43.9
Apiocrinidæ (*Carpenterocrinus*)..	565	38.1

2. Column including modified columnals, a proximale or nodals.

	Bathymetric range	Thermal range
Pentacrinitidæ	0–2900	28.7–80.0
Apiocrinidæ (*Proisocrinus*)	940	36.7
Phrynocrinidæ	508–703	38.1–40.0
Bourgueticrinidæ	62–2690	29.1–70.75

In the primitive crinoids, and in the very young (phytocrinoid stage) of the comatulids, the column is composed of an indefinite number of similar ossicles, which continuously increases during the life of the individual.

In the Articulata, however, the column typically, after attaining a certain definite number of columnals and reaching a certain definite length, abruptly ceases further growth, and the topmost columnal becomes attached to the calyx by close suture, developing into what is, to all intents and purposes, an apical calyx plate, the so-called

proximale. The so-called centrodorsal of the comatulids is such a proximale below which the original column has been discarded. In the pentacrinites the early growth is exactly as in the comatulids, but the proximale never becomes attached to the calyx; instead, new columnals are formed between it and the crown and a new stem is formed for which the original proximale serves as a terminal stem plate, and a second proximale appears beneath the calyx; this process continuing, a series of so-called nodals is formed, each of which represents, so to speak, an attempt of the column to limit itself to a definite length and to cease all further growth. In the Bourgueticrinidæ, and in most of the Apiocrinidæ, the original proximale is reduplicated, so that just beneath the calyx there is found a more or less conical structure composed of a series of proximales which increase in perfection to that just beneath the calyx.

The abrupt limitation in the growth of the column, and the formation of a proximale which becomes rigidly attached to the calyx, preventing the formation of additional columnals between it and the calyx, in contrast to the primitive method of continuous stem growth during life, is specialization through inhibition and definite limitation of the skeleton forming power of the column.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	0	2	80–75	0	1
100–200	0	2	75–70	0	2
200–300	1	2	70–65	0	2
300–400	1	2	65–60	0	2
400–500	1	2	60–55	0	2
500–600	2	3	55–50	0	2
600–700	1	3	50–45	0	2
700–800	1	3	45–40	1	2
800–900	1	2	40–35	2	4
900–1000	1	3	35–30	1	2
1000–1500	1	2	30–25	0	2
1500–2000	1	2			
2000–3000	1	2			

	1	2
Average depth	904 fathoms	797 fathoms
Average temperature	37.5° Fahr.	50.1° Fahr.

1. Column terminating in an expanded terminal stem plate.

	Bathymetric range	Thermal range
(Pentacrinitidæ)	0–2900	28.7–80.0
Apiocrinidæ	565–940	36.7–38.1
Phrynocrinidæ	508–703	38.1–40.0
Holopodidæ	5–120	71.0
Plicatocrinidæ	266–2575	31.1–43.9

2. Column without a terminal stem plate.

	Bathymetric range	Thermal range
Bourgueticrinidæ	62–2690	29.1–70.75

The columns of the earlier crinoids typically (though by no means always) terminated in an expanded base composed of a number of enlarged columnals which, in later types, became simplified as a single terminal stem plate from which the column more or less abruptly arises.

The presence of a terminal stem plate appears to be of fundamental significance, and therefore any type without it must be considered as possessing a highly specialized type of column.

The absence of a terminal stem plate indicates specialization through suppression of a fundamentally important skeletal structure.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	2	1	80–75	1	0
100–200	2	1	75–70	2	1
200–300	2	1	70–65	1	1
300–400	2	1	65–60	1	1
400–500	2	1	60–55	1	1
500–600	4	1	55–50	1	1
600–700	4	1	50–45	1	1
700–800	4	1	45–40	2	1
800–900	3	1	40–35	4	1
900–1000	3	1	35–30	2	1
1000–1500	2	1	30–25	1	1
1500–2000	2	1			
2000–3000	2	1			

	1	2
Average depth	785 fathoms	808 fathoms
Average temperature	52.0° Fahr.	44.8° Fahr.

1. Radicular cirri present.

	Bathymetric range	Thermal range
Bourgueticrinidæ	62–2690	29.1–70.75

2. Radicular cirri absent.

	Bathymetric range	Thermal range
(Pentacrinitidæ)	0–2900	28.7–80.0
Apiocrinidæ	565–940	36.7–38.1
Phrynocrinidæ	508–703	38.1–40.0
Holopodidæ	5–120	71.0
Plicatocrinidæ	266–2575	31.1–43.9

Combined with a broad spreading base composed of a mass of swollen, distorted and overgrown columnals, the early crinoids commonly possessed stout and massive radicular cirri, which were very irregular in position, and equally irregular in structure. In the Articulata this type of stem base occurs only in fossil species belonging to the family Apiocrinidæ, though a suggestion of it is found in the young of certain macrophreate comatulids, particularly those belonging to the genus *Hathrometra;* elsewhere one or other of the root systems has been suppressed.

The presence of radicular cirri appears to be of the same fundamental significance as the presence of a terminal stem plate, and therefore any type without it must be considered as possessing a highly specialized type of column.

The absence of radicular cirri, just as the absence of a terminal stem plate, indicates specialization through suppression of a fundamentally important skeletal structure.

The recent crinoids possess either radicular cirri or a terminal stem plate, but never both combined as do many of the earlier types; one or the other is always suppressed. As the suppression of either is equally an evidence of specialization, it naturally follows that we have here, in the presence or absence of the radicular cirri and the correlated absence or presence of the terminal stem plate, two categories each of which is the complement of the other, while both represent an equivalent stage in phylogenetic advancement.

Frequency at different depths		
Fathoms	1	2
0–100	1	2
100–200	1	2
200–300	1	2
300–400	1	2
400–500	1	2
500–600	1	4
600–700	1	4
700–800	1	4
800–900	1	3
900–1000	1	3
1000–1500	1	2
1500–2000	1	2
2000–3000	1	2

Frequency at different temperatures		
Degrees Fahrenheit	1	2
80–75	0	1
75–70	1	2
70–65	1	1
65–60	1	1
60–55	1	1
55–50	1	1
50–45	1	1
45–40	1	2
40–35	1	4
35–30	1	2
30–25	1	1

	1	2
Average depth	808 fathoms	785 fathoms
Average temperature	44.8° Fahr.	52.0° Fahr.

1. Cirri absent.

	Bathymetric range	Thermal range
Apiocrinidæ (*Carpenterocrinus*)	565	38.1
Phrynocrinidæ	508–703	38.1–40.0
Bourgueticrinidæ	62–2690	29.1–70.75
Holopodidæ	5–120	71.0
Plicatocrinidæ	266–2575	31.1–43.9

2. Cirri present.

	Bathymetric range	Thermal range
Pentacrinitidæ	0–2900	28.7–80.0
Apiocrinidæ (*Proisocrinus*)	940	36.7

The cirri, in contrast to the radicular cirri, properly speaking are structures primarily associated with the calyx and not with the column, though always arising from the latter. They are always associated with the existence of a proximale, or modified proximal columnal, upon which they are situated, and hence are almost entirely confined to the Articulata.

The presence of cirri is always correlated with a great reduction in the size and number of constituent elements of the column, and in the relative size and number of skeletal elements of the calyx.

While undoubtedly a new structure, the cirri by their presence always indicate a very high degree of reduction in the skeleton of the calyx and of the column, and hence are always an index of specialization through suppression of skeletal development.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	2	1	80–75	0	1
100–200	2	1	75–70	2	1
200–300	2	1	70–65	1	1
300–400	2	1	65–60	1	1
400–500	2	1	60–55	1	1
500–600	4	1	55–50	1	1
600–700	3	1	50–45	1	1
700–800	3	1	45–40	2	1
800–900	2	1	40–35	4	2
900–1000	2	2	35–30	2	1
1000–1500	2	1	30–25	1	1
1500–2000	2	1			
2000–3000	2	1			

	1	2
Average depth	783 fathoms	818 fathoms
Average temperature	47.5° Fahr.	51.3° Fahr.

III. DISK

1. Disk entirely covered with plates.

	Bathymetric range	Thermal range
Pentacrinitidæ (Zygometridæ, Calometridæ, Pentacrinitida)	0–1350	36.0–80.0
? Apiocrinidæ	565–940	36.7–38.1
Holopodidæ	5–120	71.0
Plicatocrinidæ	266–2575	31.1–43.9

2. Disk naked, or with scattered granules.

	Bathymetric range	Thermal range
Pentacrinitidæ (Comatulida, except Zygometridæ and Calometridæ)	0–2900	28.7–80.0
Phrynocrinidæ	508–703	38.1–40.0
Bourgueticrinidæ	62–2690	29.1–70.75

In the earlier crinoids belonging to the order Camerata, as in the very young of the comatulids, the disk is always entirely covered with plates, which form a solid pavement over it.

Only in the later types, chiefly in the Articulata, does this disk armament become less and less complete, eventually disappearing altogether.

The partially plated or unplated disks of many of the later crinoids furnish an example of specialization through suppression of a fundamental primitive character.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	2	2	80–75	1	1
100–200	2	2	75–70	2	2
200–300	2	2	70–65	1	2
300–400	2	2	65–60	1	2
400–500	2	2	60–55	1	2
500–600	3	3	55–50	1	2
600–700	3	3	50–45	1	2
700–800	3	3	45–40	2	2
800–900	3	2	40–35	3	3
900–1000	3	2	35–30	1	2
1000–1500	2	2	30–25	0	2
1500–2000	1	2			
2000–3000	1	2			

	1	2
Average depth	707 fathoms	791 fathoms
Average temperature	52.8° Fahr.	50.7° Fahr.

1. Orals present.

	Bathymetric range	Thermal range
Pentacrinitidæ (Calometridæ, Pentacrinitida)	0–1350	36.0–80.0
? Apiocrinidæ	565–940	36.7–38.1
Holopodidæ	5–120	71.0
Plicatocrinidæ	266–2575	31.1–43.9

2. Orals absent.

	Bathymetric range	Thermal range
Pentacrinitidæ (Comatulida, except Calometridæ)	0–2900	28.7–80.0
Phrynocrinidæ	508–703	38.1–40.0
Bourgueticrinidæ	62–2690	29.1–70.75

Correlated with the presence of a solid plating over the surface of the disk is the presence of large and definite oral plates surrounding the mouth.

These orals dwindle in size with the disintegration of the pavement on the surface of the disk, finally, like that pavement, disappearing altogether.

The disappearance of orals is an example of specialization through the suppression of a fundamental feature, and is quite comparable to the disappearance of the disk plating, with which, in a general way, it is associated.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	2	2	80–75	1	1
100–200	2	2	75–70	2	2
200–300	2	2	70–65	1	2
300–400	2	2	65–60	1	2
400–500	2	2	60–55	1	2
500–600	3	3	55–50	1	2
600–700	3	3	50–45	1	2
700–800	3	3	45–40	2	2
800–900	3	2	40–35	3	3
900–1000	3	2	35–30	1	2
1000–1500	2	2	30–25	0	2
1500–2000	1	2			
2000–3000	1	2			

	1	2
Average depth	707 fathoms	791 fathoms
Average temperature	52.8° Fahr.	50.7° Fahr.

1. Orals of different sizes.

	Bathymetric range	Thermal range
Plicatocrinidæ	266–2575	31.1–43.9

2. All five orals of the same size.

	Bathymetric range	Thermal range
Pentacrinitidæ	0–2900	28.7–80.0
Holopodidæ	5–120	71.0

In the older crinoids, in which as a rule the posterior interradius was enlarged and modified by the inclusion of plates not occurring in the other interradii, the posterior oral was as a rule larger than the other four.

In the later types which, through the suppression of features causing the differentiation of the anal interradius, exhibit a very nearly perfect pentamerous symmetry, the orals are commonly all of the same size.

The similarity of the orals is always associated with, and is an index of, a suppression of certain constituent parts of the original calyx structure, and is almost invariably associated with a reduction in the size of the orals themselves.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	0	2	80–75	0	1
100–200	0	2	75–70	0	2
200–300	1	1	70–65	0	1
300–400	1	1	65–60	0	1
400–500	1	1	60–55	0	1
500–600	1	1	55–50	0	1
600–700	1	1	50–45	0	1
700–800	1	1	45–40	1	1
800–900	1	1	40–35	1	1
900–1000	1	1	35–30	1	1
1000–1500	1	1	30–25	0	1
1500–2000	1	1			
2000–3000	1	1			

	1	2
Average depth	936 fathoms	713 fathoms
Average temperature	37.5° Fahr.	54.2° Fahr.

1. Orals with their inner edges upturned.

	Bathymetric range	Thermal range
Pentacrinitidæ (Calometridæ)	0–333	52.9–75.7
Plicatocrinidæ (except *Ptilocrinus*)	392–2575	31.1–43.9

2. Orals a spherical triangle.

	Bathymetric range	Thermal range
Pentacrinitidæ (except Calometridæ)	0–2900	28.7–80.0
Holopodidæ	5–120	71.0
Plicatocrinidæ (*Ptilocrinus*)	266–2485	35.3

In the earlier crinoids (except the Flexibilia) the orals were relatively thick plates lying in the tegmen, of which they formed part of the plated surface, and hence they acquired more or less the form of spherical triangles of very appreciable thickness. The disintegration of the orals, following that of the pavement of the disk, took place from the periphery of the oral circlet, gradually working toward the center. As the orals became thinner and thinner dorso-ventrally it naturally resulted that their edges bordering the ambulacral grooves, which were the last portions to be affected, became prominent, standing up above the general surface as thin blade-like borders parallel to the dorsoventral axis of the disk of gradually increasing height, the orals eventually disappearing not as horizontal plates lying in the tegmen but as five trough-like structures surrounding the mouth with their angles in apposition, and with their longest dimension, representing the long dimension of the trough, parallel to the dorsoventral axis. Orals of this type are characteristic of the pentacrinoid young of the macrophreate comatulids.

But while the reduction and disappearance of the orals after their complete formation as skeletal structures characteristic of the adults took this course, reduction of the orals gradually was shoved further and further back into the ontogeny of the later types so that it set in before the orals commenced to thicken. Cessation of development of the orals at this stage leaves them in the form of very thin plates lying in, and conforming in contour to, the inner angles of the interambulacral areas.

Thus the presence of thin orals lying in and conforming in contour to the inner angles of the interambulacral areas is an indication of an advanced stage of suppression of those plates, which has been shoved far forward into the ontogeny. So far as we know the orals of the stalked young of the oligophreate comatulids never develop further than this point.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	1	2	80–75	1	1
100–200	1	2	75–70	1	2
200–300	1	2	70–65	1	1
300–400	2	2	65–60	1	1
400–500	1	2	60–55	1	1
500–600	1	2	55–60	1	1
600–700	1	2	50–45	0	1
700–800	1	2	45–40	1	1
800–900	1	2	40–35	1	2
900–1000	1	2	35–30	1	1
1000–1500	1	2	30–25	0	1
1500–2000	1	2			
2000–3000	1	2			

	1	2
Average depth	596 fathoms	808 fathoms
Average temperature	$\left\{\begin{matrix}37.5^\circ \\ 65.0^\circ\end{matrix}\right\}$ Fahr.	52.9° Fahr.

1. Mouth central.

	Bathymetric range	Thermal range
Pentacrinitidæ (except Comasteridæ, and the five largest genera of Heliometrinæ)	0–2900	28.7–80.0
Phrynocrinidæ	508–703	38.1–40.0
Bourgueticrinidæ	62–2690	29.1–70.75
Holopodidæ	5–120	71.0
Plicatocrinidæ	266–2575	31.1–43.9

2. Mouth more or less excentric.

	Bathymetric range	Thermal range
Pentacrinitidæ (Comasteridæ, and the five largest genera of Heliometrinæ)	0–1062	28.7–80.0

One of the most invariable features of crinoidal structure, a necessary corollary of the primitive and fundamental pentamerous symmetry of these animals, is the central position of the mouth upon the disk.

Only in a very few types, and in these only very late in the ontogeny, do we find the mouth in an excentric position.

The migration of the mouth to an excentric position indicates a high degree of specialization which, like many similar features, is of more or less sporadic occurrence. The migration of the mouth toward an excentric position indicates the gradual suppression of the primitive and fundamental pentamerous symmetry of the crinoids.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	3	1	80–75	1	1
100–200	3	1	75–70	3	1
200–300	3	1	70–65	2	1
300–400	3	1	65–60	2	1
400–500	3	1	60–55	2	1
500–600	4	1	55–50	2	1
600–700	4	1	50–45	2	1
700–800	4	1	45–40	3	1
800–900	3	1	40–35	4	1
900–1000	3	1	35–30	3	1
1000–1500	3	1	30–25	2	1
1500–2000	3	0			
2000–3000	3	0			

	1	2
Average depth	775 fathoms	568 fathoms
Average temperature	50.0° Fahr.	52.5° Fahr.

IV. ARMS

1. Arms composed of a linear series of ossicles, without IBr series.

	Bathymetric range	Thermal range
Pentacrinitidæ (Pentametrocrinidæ and part of Atelecrinidæ)	103–1800	33.5–60.6
Plicatocrinidæ (except *Calamocrinus*)	266–2575	31.1–43.9

2. Arms dividing one or more times, or, if undivided, with IBr series.

	Bathymetric range	Thermal range
Pentacrinitidæ (except Pentametrocrinidæ and part of Atelecrinidæ)	0–2900	28.7–80.0
Apiocrinidæ	565–940	36.7–38.1
Phrynocrinidæ	508–703	38.1–40.0
Bourgueticrinidæ	62–2690	29.1–70.75
Holopodidæ	5–120	71.0
Plicatocrinidæ (*Calamocrinus*)	392–782	38.5–43.9

Whatever may have been the ultimate origin of the crinoid arm as a structure, the immediate ancestor of the recent types certainly possessed arms composed of an undifferentiated linear series of ossicles.

Subsequently this simple type of arm became modified through the interpolation between the arm base and the radial of the so-called IBr series, a pair of ossicles which is in reality a more or less perfect reduplication of the radial (corresponding to the IBr_2) and the infraradial (corresponding to the IBr_1).

The presence of IBr series is rendered possible only by a very considerable reduction in the development of the calyx. The arms arise from the border of the disk, and are outgrowths of which the dorsal skeletal structures are derivatives from the skeletal structures of the sides of the calyx cup, while the ventral structures, the ambulacral grooves, water, blood, muscle and ventral nerve systems, are outgrowths from the corresponding structures on the disk which have extended themselves outward over the dorsal skeletal structures as a support. Being in part derived from the lateral body wall and in part an outgrowth from the ventral surface, the arms necessarily must maintain their original position on the edge of the disk. In the reduction of the calyx from the primitive condition of a cup entirely enclosing the visceral mass dorsally and laterally to the form of a small cap covering only the dorsal pole of the visceral mass, or of a platform upon which the visceral mass rests, the arms, as much a part of the disk as of the dorsal skeletal structure, are unable to maintain their original connection with the now greatly reduced radials. The growing gap between the arm bases and the radials is filled not by a dorsalward extension of the arm bases, but by the formation of an entirely new pair of plates, the IBr series, between the radials and the arm bases, which serve to maintain the connection, and which are in origin and in structure a more or less perfect reduplication of the now atrophied radial and infraradial (or possibly infrabasal). The presence of IBr series is therefore a certain indication of the suppression of other more extensive skeletal structures, and is therefore an indication of specialization through suppression. In this respect the presence of IBr series is of the same significance as the presence of cirri, which always indicate and accompany a suppression of development in the column. As the specialization of the column through suppression of its growth is correlated with the specialization of the calyx through suppression of its development, it is only natural that we should find the development of cirri more or less closely correlated with the development of IBr (and additional comparable) series.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	0	3	80–75	0	1
100–200	1	3	75–70	0	3
200–300	2	2	70–65	0	2
300–400	2	3	65–60	1	2
400–500	2	3	60–55	1	2
500–600	2	5	55–50	1	2
600–700	2	5	50–45	1	2
700–800	2	5	45–40	2	3
800–900	2	3	40–35	2	5
900–1000	2	3	35–30	2	2
1000–1500	2	2	30–25	0	2
1500–2000	2	2			
2000–3000	1	2			

	1	2
Average depth	795 fathoms	723 fathoms
Average temperature	37.0° Fahr.	42.9° Fahr.

1. Arms with IBr series in which the outer element is axillary.

	Bathymetric range	Thermal range
Pentacrinitidæ (except *Eudiocrinus* and *Metacrinus*)	0–2900	28.7–80.0
Apiocrinidæ	565–940	36.7–38.1
Bourgueticrinidæ (*Ilycrinus, Bathycrinus, Monachocrinus*)	743–2690	30.9–40.0
Holopodidæ	5–120	71.0

2. Arms with IBr series in which the outer element is not axillary.

	Bathymetric range	Thermal range
Pentacrinitidæ (*Eudiocrinus* and *Metacrinus*)	22–630	39.5–71.0
Bourgueticrinidæ (*Democrinus, Bythocrinus, Rhizocrinus*)	61–1300	31.8–48.7

In the course of the development of the IBr series it came about that the outer element (the IBr_2) is normally axillary, bearing two exactly similar arms instead of a single arm as in the case of an arm-bearing radial.

Occasionally it happens that the IBr_2 is not axillary, but gives rise to a linear series of ossicles, like the primitive radial. A more or less common meristic variation in many diverse types, this feature has in others become fixed and invariable.

The reduction of the IBr_2 from its normal condition of an axillary to an ossicle giving rise to a simple linear series of ossicles, with the

resultant loss of half of the number of arms, is an illustration of specialization through suppression.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	2	2	80–75	1	0
100–200	2	2	75–70	2	1
200–300	1	2	70–65	1	1
300–400	1	2	65–60	1	1
400–500	1	2	60–55	1	1
500–600	2	2	55–50	1	1
600–700	2	2	50–45	1	2
700–800	3	1	45–40	1	2
800–900	3	1	40–35	3	2
900–1000	3	1	35–30	2	1
1000–1500	2	1	30–25	1	0
1500–2000	2	0			
2000–3000	2	0			

	1	2
Average depth	865 fathoms	483 fathoms
Average temperature	50.5° Fahr.	50.0° Fahr.

1. The first bifurcation is at a more or less indefinite distance beyond the second post-radial ossicle.

	Bathymetric range	Thermal range
Pentacrinitidæ (*Metacrinus*)	30–630	39.5–71.0
Phrynocrinidæ	508–703	38.1–40.0
Plicatocrinidæ	266–2575	31.1–43.9

2. The first bifurcation is on the second post-radial ossicle.

	Bathymetric range	Thermal range
Pentacrinitidæ (except *Metacrinus*)	0–2900	28.7–80.0
Apiocrinidæ	565–940	36.7–38.1
Bourgueticrinidæ	62–2690	29.1–70.75
Holopodidæ	5–120	71.0

In the earlier crinoid types, especially before the formation of definite IBr series, the bifurcation of the arms commenced at a more or less indefinite distance from the radials.

Later the number of plates intervening between the radials and the first axillary became reduced to one only.

The reduction of the number of plates between the radials and the first axillary from several to one only indicates specialization through the suppression of useless skeletal structures.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	1	3	80–75	0	1
100–200	1	3	75–70	1	3
200–300	2	2	70–65	1	2
300–400	2	2	65–60	1	2
400–500	2	2	60–55	1	2
500–600	3	3	55–50	1	2
600–700	3	3	50–45	1	2
700–800	2	3	45–40	2	2
800–900	1	3	40–35	3	3
900–1000	1	3	35–30	1	2
1000–1500	1	2	30–25	0	2
1500–2000	1	2			
2000–3000	1	2			

	1	2
Average depth	700 fathoms	756 fathoms
Average temperature	49.1° Fahr.	51.6° Fahr.

1. A suture (or pseudo-syzygy) between the ossicles of the IBr series.

	Bathymetric range	Thermal range
Pentacrinitidæ (*Comatula, Comaster,* Zygometridæ, Pentacrinitida)	0–1350	36.0–80.0
Phrynocrinidæ	508–703	38.1–40.0
Plicatocrinidæ	266–2575	31.1–43.9

2. A ligamentous articulation (or synarthry) between the ossicles of the IBr series.

	Bathymetric range	Thermal range
Pentacrinitidæ (except *Comatula, Comaster,* Zygometridæ, Pentacrinitida)	0–2900	28.7–80.0
Apiocrinidæ	565–940	36.7–38.1
Bourgueticrinidæ	62–2690	29.1–70.75
Holopodidæ	5–120	71.0

So far as can be ascertained, the union between the plates of the IBr series in the earlier crinoids was by means of a more or less featureless suture.

This suture in the later types became developed into a very distinctive ligamentous articulation known as the synarthry, composed of two lateral ligament bundles separated by a strong dorsoventral ridge running entirely across the apposed articular faces.

The development of a union composed of large and definite ligament bundles from a union of scattered and diffuse fibers occupying a much greater surface indicates a great reduction in the skeleton

whereby the original fibers have been collected and compressed into compact bundles, and is therefore an indication of development by suppression of the skeleton forming power.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	1	3	80–75	1	1
100–200	1	3	75–70	1	3
200–300	2	2	70–65	1	2
300–400	2	2	65–60	1	2
400–500	2	2	60–55	1	2
500–600	3	3	55–50	1	2
600–700	3	3	50–45	1	2
700–800	3	3	45–40	2	2
800–900	2	3	40–35	3	3
900–1000	2	3	35–30	1	2
1000–1500	2	2	30–25	0	2
1500–2000	1	2			
2000–3000	1	2			

	1	2
Average depth	740 fathoms	755 fathoms
Average temperature	51.3° Fahr.	51.6° Fahr.

1. Division series composed of an irregular number of ossicles.

	Bathymetric range	Thermal range
Pentacrinitidæ (*Metacrinus, Isocrinus*)	5–667	39.5–71.0
Phrynocrinidæ	508–703	38.1–40.0
Plicatocrinidæ	266–2575	31.1–43.9

2. All of the division series composed of a fixed number of segments.

	Bathymetric range	Thermal range
Pentacrinitidæ (except *Metacrinus* and *Isocrinus*)	0–2900	28.7–80.0
Apiocrinidæ	565–940	36.7–38.1
Bourgueticrinidæ	62–2690	29.1–70.75
Holopodidæ	5–120	71.0

Like the first division series, the succeeding division series in the more primitive crinoid types were composed of a variable and irregular number of ossicles.

After the evolution of the IBr system, of two ossicles only, interpolated between the radials and the arm bases, this system, as the calyx continued to decrease in size, became developed and extended so as to supplant all of the succeeding division series.

The substitution of the primitive division series of a variable and irregular number of ossicles by a system made up of units of two ossicles each, resulting in a great diminution in the number of elements necessary to support a given number of ultimate arm branches, is an example of specialization through suppression of superfluous skeletal elements.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	1	3	80–75	0	1
100–200	1	3	75–70	1	3
200–300	2	2	70–65	1	2
300–400	2	2	65–60	1	2
400–500	2	2	60–55	1	2
500–600	3	3	55–50	1	2
600–700	3	3	50–45	1	2
700–800	2	3	45–40	2	2
800–900	1	3	40–35	3	3
900–1000	1	3	35–30	1	2
1000–1500	1	2	30–25	0	2
1500–2000	1	2			
2000–3000	1	2			

	1	2
Average depth	698 fathoms	756 fathoms
Average temperature	49.1° Fahr.	51.6° Fahr.

1. The arms occupy only a portion of the distal border of the radials.

	Bathymetric range	Thermal range
Pentacrinitidæ (certain genera of Calometridæ)	0–333	52.9–75.7
Plicatocrinidæ	266–2575	31.1–43.9

2. The arms occupy the entire distal border of the radials.

	Bathymetric range	Thermal range
Pentacrinitidæ (except certain genera of Calometridæ)	0–2900	28.7–80.0
Apiocrinidæ	565–940	36.7–38.1
Phrynocrinidæ	508–703	38.1–40.0
Bourgueticrinidæ	62–2690	29.1–70.75
Holopodidæ	5–120	71.0

In the primitive crinoids and in the young of the comatulids the calyx more or less extensively encloses the visceral mass dorsally and laterally, and the arms occupy only a relatively small part of the distal border of the radials.

But in the more specialized types and in the fully grown comatulids the reduction in size of the calyx and its retreat toward the dorsal pole causes the arms, which always remain of approximately the same relative proportions, gradually to come to occupy the entire distal border of the radials.

The occupation by the arm bases of the entire distal border of the radials is an indication of the reduction in size of the radials and other calyx plates, and hence must be regarded as indicating specialization through suppression or atrophy of the skeletal structures.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	1	3	80–75	1	1
100–200	1	3	75–70	1	3
200–300	2	2	70–65	1	2
300–400	2	2	65–60	1	2
400–500	1	2	60–55	1	2
500–600	1	4	55–50	1	2
600–700	1	4	50–45	0	2
700–800	1	4	45–40	1	2
800–900	1	3	40–35	1	4
900–1000	1	3	35–30	1	2
1000–1500	1	2	30–25	0	2
1500–2000	1	2			
2000–3000	1	2			

	1	2
Average depth	612 fathoms	747 fathoms
Average temperature	{37.5° / 65.0°} Fahr.	51.0° Fahr.

1. All the arms of equal length.

	Bathymetric range	Thermal range
Pentacrinitidæ (except Comasteridæ)	0–2900	28.7–80.0
Apiocrinidæ	565–940	36.7–38.1
Phrynocrinidæ	508–703	38.1–40.0
Bourgueticrinidæ	62–2690	29.1–70.75
Plicatocrinidæ	266–2575	31.1–43.9

2. The posterior arms dwarfed.

	Bathymetric range	Thermal range
Pentacrinitidæ (Comasteridæ)	0–830	44.5–80.0
Holopodidæ	5–120	71.0

The crinoids being primarily and fundamentally pentamerous, all five of their arms (or groups of arms) are primarily of equal size and length.

But in certain types the posterior arms (in the Palæozoic usually the anterior), particularly the left posterior, are more or less dwarfed or atrophied, this resulting in a more or less marked bilateral symmetry in which the anteroposterior axis may pass either through the left posterior arm and the right anterior interambulacral area, or through the anterior arm and the posterior interambulacral area.

The dwarfing or atrophy of one or both of the posterior arms is specialization through partial suppression of the normal arm development.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	2	2	80–75	1	1
100–200	2	2	75–70	2	2
200–300	3	1	70–65	2	1
300–400	3	1	65–60	2	1
400–500	3	1	60–55	2	1
500–600	5	1	55–50	2	1
600–700	5	1	50–45	2	1
700–800	5	1	45–40	3	1
800–900	4	1	40–35	5	0
900–1000	4	0	35–30	3	0
1000–1500	3	0	30–25	2	0
1500–2000	3	0			
2000–3000	3	0			

	1	2
Average depth	822 fathoms	359 fathoms
Average temperature	48.6° Fahr.	61.4° Fahr.

1. All the arms terminate in a growing tip.

	Bathymetric range	Thermal range
Pentacrinitidæ (except Comasteridæ)	0–2900	28.7–80.0
Apiocrinidæ	565–940	36.7–38.1
Phrynocrinidæ	508–703	38.1–40.0
Bourgueticrinidæ	62–2690	29.1–70.75
Holopodidæ	5–120	71.0
Plicatocrinidæ	266–2575	31.1–43.9

2. Some of the arms terminate in a pair of pinnules.

	Bathymetric range	Thermal range
Pentacrinitidæ (Comasteridæ)	0–830	44.5–80.0

Normally in the crinoids the arms grow continually throughout life, and the arms therefore always terminate in a growing tip.

But in case arm growth is arrested it frequently happens that a definite perfected arm type is acquired which terminates in a pair of pinnules and is capable of no further development.

The presence of (posterior) arms terminating in a pair of pinnules indicates specialization through more or less extensive suppression of the normal arm growth.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	3	1	80–75	1	1
100–200	3	1	75–70	3	1
200–300	2	1	70–65	2	1
300–400	3	1	65–60	2	1
400–500	3	1	60–55	2	1
500–600	5	1	55–50	2	1
600–700	5	1	50–45	2	1
700–800	5	1	45–40	3	1
800–900	3	1	40–35	5	0
900–1000	3	0	35–30	2	0
1000–1500	2	0	30–25	2	0
1500–2000	2	0			
2000–3000	2	0			

	1	2
Average depth	723 fathoms	450 fathoms
Average temperature	42.9° Fahr.	60.0° Fahr.

1. All the arms are provided with ambulacral grooves.

	Bathymetric range	Thermal range
Pentacrinitidæ (except Comasteridæ)	0–2900	28.7–80.0
Apiocrinidæ	565–940	36.7–38.1
Phrynocrinidæ	508–703	38.1–40.0
Bourgueticrinidæ	62–2690	29.1–70.75
Holopodidæ	5–120	71.0
Plicatocrinidæ	266–2575	31.1–43.9

2. The posterior arms are without ambulacral grooves.

	Bathymetric range	Thermal range
Comasteridæ	0–830	44.5–80.0

In the crinoids all of the arms are normally provided ventrally with ambulacral grooves.

From the posterior arms of certain types, which always are correlatively more or less dwarfed, these ambulacral grooves may be absent.

The absence of ambulacral grooves on the posterior arms (which may involve as many as three of the five radii) indicates specializa-

tion through the suppression of one of the most fundamental elements of the arm structure.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	3	1	80–75	1	1
100–200	3	1	75–70	3	1
200–300	2	1	70–65	2	1
300–400	3	1	65–60	2	1
400–500	3	1	60–55	2	1
500–600	5	1	55–50	2	1
600–700	5	1	50–45	2	1
700–800	5	1	45–40	3	1
800–900	3	1	40–35	5	0
900–1000	3	0	35–30	2	0
1000–1500	2	0	30–25	2	0
1500–2000	2	0			
2000–3000	2	0			

	1	2
Average depth	723 fathoms	450 fathoms
Average temperature	42.9° Fahr.	60.0° Fahr.

V. PINNULES

1. Pinnules, at least the proximal, more or less sharply triangular in cross section.

	Bathymetric range	Thermal range
Pentacrinitidæ (except Macrophreata)	0–1600	34.2–80.0
Apiocrinidæ	565–940	36.7–38.1
Phrynocrinidæ	508–703	38.1–40.0
Bourgueticrinidæ	62–2690	29.1–70.75
Holopodidæ	5–120	71.0
Plicatocrinidæ	266–2575	31.1–43.9

2. Pinnules circular or elliptical in cross section.

	Bathymetric range	Thermal range
Pentacrinitidæ (Macrophreata)	0–2900	28.7–79.1

In all of the earlier crinoids in which the structure of the pinnules can be made out these organs are found to be prismatic in form and more or less sharply triangular in cross section, the ambulacral groove occupying a side opposite to a sharp (dorsal) ridge.

In a few highly specialized types the pinnules, instead of being strongly prismatic and triangular in cross section, are more or less cylindrical and circular or elliptical in cross section, with very slender segments and swollen joints.

In the change from the prismatic to the cylindrical type the pinnules lose a very large part of the calcareous substance, becoming very

slender; and hence we may look upon this change as correlated with an increasing suppression of the skeleton forming power.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	3	1	80–75	1	1
100–200	3	1	75–70	3	1
200–300	3	1	70–65	2	1
300–400	3	1	65–60	2	1
400–500	3	1	60–55	2	1
500–600	5	1	55–50	2	1
600–700	5	1	50–45	2	1
700–800	5	1	45–40	3	1
800–900	4	1	40–35	5	1
900–1000	4	1	35–30	3	1
1000–1500	3	1	30–25	1	1
1500–2000	3	1			
2000–3000	2	1			

	1	2
Average depth	754 fathoms	808 fathoms
Average temperature	50.4° Fahr.	52.5° Fahr.

1. All of the pinnules similar.

	Bathymetric range	Thermal range
Pentacrinitidæ (Ptilometrinæ, Atelecrinidæ, Pentacrinitida)	0–1350	36.0–80.0
Apiocrinidæ	565–940	36.7–38.1
Phrynocrinidæ	508–703	38.1–40.0
Bourgueticrinidæ	62–2690	29.1–70.75
Holopodidæ	5–120	71.0
Plicatocrinidæ	266–2575	31.1–43.9

2. The proximal pinnules modified.

	Bathymetric range	Thermal range
Pentacrinitidæ (Comatulida, except Ptilometrinæ and Atelecrinidæ)	0–2900	28.7–80.0

So far as we know the earlier crinoids, like the young comatulids before the appearance of P_1, had all the pinnules similar, except in the cases in which the proximal segments of the lower pinnules were embedded in the calyx wall, when these were enlarged and broadened.

But in the dominant types to-day the proximal pinnules are almost always modified, having lost their original significance and adopted instead the function of slender tactile or stout protective organs.

The modification of the proximal pinnules is always associated with the loss not only of the ambulacral grooves and the associated structures, but also of the genital organs; and it therefore is possible

to consider it as an indication of specialization through suppression of all of the functions of pinnules, which has permitted a radical change in their structure.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	3	1	80–75	1	1
100–200	3	1	75–70	3	1
200–300	3	1	70–65	2	1
300–400	3	1	65–60	2	1
400–500	3	1	60–55	2	1
500–600	5	1	55–50	2	1
600–700	5	1	50–45	2	1
700–800	5	1	45–40	3	1
800–900	4	1	40–35	5	1
900–1000	4	1	35–30	2	1
1000–1500	3	1	30–25	1	1
1500–2000	2	1			
2000–3000	2	1			

	1	2
Average depth	621 fathoms	808 fathoms
Average temperature	51.1° Fahr.	52.5° Fahr.

1. Pinnulation of the arm bases more or less deficient.

	Bathymetric range	Thermal range
Pentacrinitidæ (part of Capillasterinæ, Colobometridæ, Zenometrinæ, Pentametrocrinidæ and Atelecrinidæ, and all of the Perometrinæ)	0–1050	37.0–80.0
Phrynocrinidæ	508–703	38.1–40.0
Bourgueticrinidæ	62–2690	29.1–70.75
Plicatocrinidæ	266–2575	31.1–43.9

2. All of the proximal pinnules present.

	Bathymetric range	Thermal range
Pentacrinitidæ (except part of Capillasterinæ, Colobometridæ, Zenometrinæ, Pentametrocrinidæ, and Atelecrinidæ, and the Perometrinæ)	0–2900	28.7–80.0
Apiocrinidæ	565–940	36.7–38.1
Holopodidæ	5–120	71.0

In the earlier crinoids all of the pinnules were commonly present, but with the decrease in the size of the visceral mass and the corresponding increase in the size and in the length of the arms which we are, in a general way, able to trace from the earlier to the later types,

the arm bases became more or less crowded together, so that the development of pinnules on the earlier brachials became impossible.

With the further reduction of the calyx, which chiefly involved the turning outward of the radials so that ultimately they attained a position at right angles to instead of parallel with the dorsoventral axis of the animal, the arms progressively became more and more widely separated, and then, step by step, the proximal pinnules were again able to develop.

Although originally the crinoids possessed all of the proximal pinnules, the primitive condition of the immediate ancestors of the groups to which the recent types belong was a deficient pinnulation of the arm bases. As the reappearance of the pinnules on the arm bases was made possible by, and is therefore directly correlated with, the more advanced stages in the reduction of the calyx, perfection of the proximal pinnulation is in reality an evidence of specialization through a reduction of the more fundamental elements of the skeleton.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	2	2	80–75	1	1
100–200	2	2	75–70	2	2
200–300	3	1	70–65	2	1
300–400	3	1	65–60	2	1
400–500	3	1	60–55	2	1
500–600	4	2	55–50	2	1
600–700	4	2	50–45	2	1
700–800	4	2	45–40	3	1
800–900	3	2	40–35	4	2
900–1000	3	2	35–30	2	1
1000–1500	3	1	30–25	1	1
1500–2000	2	1			
2000–3000	2	1			

	1	2
Average depth	763 fathoms	722 fathoms
Average temperature	50.7° Fahr.	52.9° Fahr.

1. Side- and covering-plates highly developed.

	Bathymetric range	Thermal range
Pentacrinitidæ (Calometridæ, Thalassometridæ, Charitometridæ, and Pentacrinitida)	0–1600	34.2–75.7
Apiocrinidæ	565–940	36.7–38.1
Bourgueticrinidæ	62–2690	29.1–70.75
Holopodidæ	5–120	71.0
Plicatocrinidæ	266–2575	31.1–43.9

2. Side- and covering-plates rudimentary.

	Bathymetric range	Thermal range
Pentacrinitidæ (except Calometridæ, Thalassometridæ, Charitometridæ, and Pentacrinitida) ...	0–2900	28.7–80.0
Phrynocrinidæ	508–703	38.1–40.0

Side- and covering-plates, in one form or another, are of almost universal occurrence among the earlier crinoids.

In certain of the later and more specialized types the development of the plates has been more or less completely suppressed.

In this we see a clear example of specialization through suppression of a fundamental structure.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	2	1	80–75	1	1
100–200	2	1	75–70	2	1
200–300	3	1	70–65	2	1
300–400	3	1	65–60	2	1
400–500	3	1	60–55	2	1
500–600	4	2	55–50	2	1
600–700	4	2	50–45	2	1
700–800	4	2	45–40	3	1
800–900	4	1	40–35	4	2
900–1000	4	1	35–30	3	1
1000–1500	3	1	30–25	1	1
1500–2000	3	1			
2000–3000	2	1			

	1	2
Average depth	794 fathoms	778 fathoms
Average temperature	50.0° Fahr.	51.2° Fahr.

1. All of the pinnules beyond the oral provided with ambulacral grooves.

	Bathymetric range	Thermal range
Pentacrinitidæ (except Comasteridæ and Charitometridæ)	0–2900	28.7–80.0
Apiocrinidæ	565–940	36.7–38.1
Phrynocrinidæ	508–703	38.1–40.0
Bourgueticrinidæ	62–2690	29.1–70.75
Holopodidæ	5–120	71.0
Plicatocrinidæ	266–2575	31.1–43.9

2. Some or all of the pinnules on certain arms without ambulacral grooves.

	Bathymetric range	Thermal range
Pentacrinitidæ (Comasteridæ, Charitometridæ)	0–1200	39.5–80.0

Primarily all the pinnules on a crinoid arm are similar, and all are provided with ambulacral grooves. In many of the later types, however, the ambulacral grooves on the proximal pinnules have been suppressed.

In other late types not only have the ambulacral furrows and associated structures been suppressed on the proximal pinnules, but also they have disappeared from the genital, and in many cases from all, the pinnules.

The disappearance of the ambulacral grooves and associated structures from the genital and distal pinnules is an instance of specialization through suppression of a fundamental structure.

Frequency at different depths			Frequency at different temperatures		
Fathoms	1	2	Degrees Fahrenheit	1	2
0–100	3	1	80–75	1	1
100–200	3	1	75–70	3	1
200–300	3	1	70–65	2	1
300–400	3	1	65–60	2	1
400–500	3	1	60–55	2	1
500–600	5	1	55–50	2	1
600–700	5	1	50–45	2	1
700–800	5	1	45–40	3	1
800–900	4	1	40–35	5	1
900–1000	4	1	35–30	3	0
1000–1500	3	1	30–25	2	0
1500–2000	3	0			
2000–3000	3	0			

	1	2
Average depth	822 fathoms	568 fathoms
Average temperature	49.5° Fahr.	57.5° Fahr.

VI. GENERAL

1. Skeleton composed of more than a million ossicles.

	Bathymetric range	Thermal range
Pentacrinitidæ (part of Capillasterinæ, Comasterinæ, Zygometridæ, Himerometridæ, Mariametridæ, Colobometridæ, and Heliometrinæ, and Pentacrinitida)	0–1350	28.7–80.0

2. Skeleton composed of less than a million ossicles.

	Bathymetric range	Thermal range
Pentacrinitidæ (except part of Capillasterinæ, Comasterinæ, Zygometridæ, Himerometridæ, Mariametridæ, Colobometridæ, and Heliometrinæ, and Pentacrinitida)	0–2900	28.7–80.0
Apiocrinidæ	565–940	36.7–38.1
Phrynocrinidæ	508–703	38.1–40.0
Bourgueticrinidæ	62–2690	29.1–70.75
Holopodidæ	5–120	71.0
Plicatocrinidæ	266–2575	31.1–43.9

In the older crinoids the skeleton was usually composed of an enormous number of ossicles.

In the later and more specialized types the individual skeletal elements are as a rule very much less in number.

This is a good example of specialization through suppression.

Frequency at different depths		
Fathoms	1	2
0–100	1	3
100–200	1	3
200–300	1	3
300–400	1	3
400–500	1	3
500–600	1	5
600–700	1	5
700–800	1	5
800–900	1	4
900–1000	1	4
1000–1500	1	3
1500–2000	0	3
2000–3000	0	3

Frequency at different temperatures		
Degrees Fahrenheit	1	2
80–75	1	1
75–70	1	3
70–65	1	2
65–60	1	2
60–55	1	2
55–50	1	2
50–45	1	2
45–40	1	3
40–35	1	5
35–30	1	3
30–25	1	2

	1	2
Average depth	568 fathoms	822 fathoms
Average temperature	52.5° Fahr.	49.5° Fahr.

THE FAMILIES OF RECENT CRINOIDS, WITH THE CHARACTERS, AS PREVIOUSLY GIVEN, PRESENTED BY EACH

In the following pages each of the families including recent crinoids is given, together with the characters as just described which it presents.

PENTACRINITIDÆ

Calyx

2. Calyx forming a platform upon which the viscera rest, more or less supported by the arm bases.
2. Calyx reduced by the eversion and imbrication of the calyx plates.
    1. Basals present (minority).
    2. Basals absent (majority).
1. Five basals.
    1. Basals separate (minority).
    2. Basals fused into a single calcareous plate (majority).
    1. Infrabasals present as individual plates (minority).
    2. Infrabasals absent, or fused with other plates (majority).
    1. Five radials (majority).
    2. Ten radials (minority).
    1. Interradials present (minority).
    2. Interradials absent (majority).
    1. Anal *x*, bearing a process, present (minority).
    2. Anal *x*, bearing a process, absent (majority).
    1. Interbrachials present (large minority).
    2. Interbrachials absent (small majority).

Column

2. Original column discarded in early life.
2. Column not composed of short cylindrical ossicles with radial crenellæ.
2. Column including modified columnals, a proximale or nodals.
(1. Column terminating in an expanded terminal stem plate.)
(2. Radicular cirri absent.)
2. Cirri present.

Disk

    1. Disk entirely covered with plates (minority).
    2. Disk naked, or with scattered granules (majority).
    1. Orals present (minority).
    2. Orals absent (majority).
2. All five orals of the same size.
    1. Orals with their inner edges upturned (minority).
    2. Orals a spherical triangle (majority).
    1. Mouth central (majority).
    2. Mouth more or less excentric (minority).

Arms

1. Arms composed of a linear series of ossicles, without IBr series (minority).
2. Arms dividing one or more times, or, if undivided, with IBr series (majority).
1. Arms with IBr series in which the outer element is axillary (majority).
2. Arms with IBr series in which the outer element is not axillary (minority).
1. The first bifurcation is at a more or less indefinite distance beyond the second post-radial ossicle (minority).
2. The first bifurcation is on the second post-radial ossicle (majority).
1. A suture between the ossicles of the IBr series (minority).
2. A ligamentous articulation in the IBr series (majority).
1. Division series composed of an irregular number of elements (minority).
2. Division series composed of a fixed number of elements (majority).
1. The arms occupy only a portion of the border of the radials (minority).
2. The arms occupy the entire distal border of the radials (majority).
1. All the arms of equal length (majority).
2. The posterior arms dwarfed (minority).
1. All the arms terminate in a growing tip (majority).
2. Some of the arms end in a pair of pinnules (minority).
1. All of the arms are provided with ambulacral grooves (majority).
2. The posterior arms are without ambulacral grooves (minority).

Pinnules

1. Pinnules, at least the proximal, more or less sharply triangular in cross section (majority).
2. Pinnules circular or elliptical in cross section (minority).
1. All of the pinnules similar (minority).
2. The proximal pinnules modified (majority).
1. Pinnulation of the arm bases more or less deficient (minority).
2. All of the proximal pinnules present (majority).
1. Side- and covering-plates highly developed (minority).

2. Side- and covering-plates rudimentary (majority).
1. All of the pinnules beyond the oral provided with ambulacral grooves (majority).
2. Some or all of the pinnules on certain arms without ambulacral grooves (minority).

General

1. Skeleton composed of more than a million ossicles (minority).
2. Skeleton composed of less than a million ossicles (majority).

APIOCRINIDÆ

Calyx

2. Calyx forming a platform upon which the viscera rest more or less supported by the arm bases.
2. Calyx reduced by the eversion and imbrication of the calyx plates.
1. Basals present.
1. Five basals.
1. Basals separate.
1. Five radials.
2. Interradials absent.
2. Anal x absent.
2. Interbrachials absent.

Column

1. Entire column present.
1. Column jointed.
2. Column not composed of short cylindrical ossicles with radial crenellæ.
    1. Column composed of a single type of columnals, without a proximale or nodals (half).
    2. Column including modified columnals, a proximale or nodals (half).
1. Column terminating in an expanded terminal stem plate.
2. Radicular cirri absent.
    1. Cirri absent (half).
    2. Cirri present (half).

Arms.

2. Arms dividing one or more times, with IBr series.
1. Arms with IBr series in which the outer element is axillary.
2. The first bifurcation is on the second post-radial ossicle.

2. A ligamentous articulation between the ossicles of the IBr series.
2. Division series composed of a fixed number of ossicles.
2. The arms occupy the entire distal border of the radials.
1. All the arms of equal length.
1. All the arms terminate in a growing tip.
1. All the arms are provided with ambulacral grooves.

Pinnules

1. Pinnules more or less sharply triangular in cross section.
1. All of the pinnules similar.
2. All of the proximal pinnules present.
1. Side- and covering-plates highly developed.
1. All of the pinnules provided with ambulacral grooves.

General

2. Skeleton composed of less than a million ossicles.

PHRYNOCRINIDÆ

Calyx

2. Calyx forming a platform upon which the viscera rest, more or less supported by the arm bases.
    1. Calyx reduced by the moving inward of all the calyx plates (half).
    2. Calyx reduced by the eversion and imbrication of the calyx plates (half).
1. Basals present.
1. Five basals.
1. Basals separate.
1. Five radials.
2. Interradials absent.
2. Anal *x* absent.
2. Interbrachials absent.

Column

1. Entire column present.
1. Column jointed.
2. Column not composed of short cylindrical ossicles with radial crenellæ.
2. Column including modified columnals, a proximale or nodals.
1. Column terminating in an expanded terminal stem plate.
2. Radicular cirri absent.
1. Cirri absent.

Disk

2. Disk naked.
2. Orals absent.
1. Mouth central.

Arms

2. Arms dividing one or more times, but without IBr series.
1. The first bifurcation is at a more or less indefinite distance beyond the second post-radial ossicle.
1. A suture between the ossicles of the IBr series.
1. Division series composed of an irregular number of ossicles.
2. The arms occupy the entire distal border of the radials.
1. All the arms of equal length.
1. All the arms terminating in a growing tip.
1. All the arms provided with ambulacral grooves.

Pinnules

1. Pinnules more or less sharply triangular in cross section.
1. All of the pinnules similar.
1. Pinnulation of the arm bases more or less deficient.
2. Side- and covering-plates rudimentary.
1. All of the pinnules provided with ambulacral grooves.

General

2. Skeleton composed of less than a million ossicles.

BOURGUETICRINIDÆ

Calyx

2. Calyx forming a platform upon which the viscera rest, more or less supported by the arm bases.
1. Calyx reduced by the moving inward of all the calyx plates.
1. Basals present.
1. Five basals.
    1. Basals separate (half).
    2. Basals fused into a single calcareous element (half).
2. No infrabasals.
1. Five radials.
2. Interradials absent.
2. Anal x absent.
2. Interbrachials absent.

Column

1. Entire column present.
1. Column jointed.
2. Column not composed of short cylindrical ossicles with radial crenellæ.
2. Column including modified columnals, a proximale or nodals.
2. Column without a terminal stem plate.
1. Radicular cirri present.
1. Cirri absent.

Disk

2. Disk naked.
2. Orals absent.
1. Mouth central.

Arms

2. Arms with IBr series.
1. Arms with IBr series in which the outer element is axillary.
2. The first bifurcation is on the second post-radial ossicle.
2. A ligamentous articulation between the ossicles of the IBr series.
2. Division series composed of a fixed number of ossicles.
2. The arms occupy the entire distal border of the radials.
1. All the arms are of equal length.
1. All the arms terminate in a growing tip.

Pinnules

1. Pinnules more or less sharply triangular in cross section.
1. All of the pinnules similar.
1. Pinnulation of the arm bases more or less deficient.
1. Side- and covering-plates highly developed.
1. All of the pinnules provided with ambulacral grooves.

General

2. Skeleton composed of less than a million ossicles.

HOLOPODIDÆ

Calyx

1. Calyx in the form of a cup, protecting the viscera dorsally and laterally.
2. No basals.
2. No infrabasals.

1. Five radials.
2. Interradials absent.
2. Anal *x* absent.
2. Interbrachials absent.

Column

1. Entire column present.
2. Column unjointed.
2. Column not composed of short cylindrical ossicles with radial crenellæ.
1. Column terminating in an expanded terminal stem plate.
2. Radicular cirri absent.
1. Cirri absent.

Disk

1. Disk entirely covered with plates.
1. Orals present.
2. All five orals of the same size.
2. Orals a spherical triangle.
1. Mouth central.

Arms

2. Arms dividing once, with IBr series.
1. Arms with IBr series in which the outer element is axillary.
2. The first bifurcation is on the second post-radial ossicle.
2. A ligamentous articulation between the elements of the IBr series.
2. Division series composed of a fixed number of ossicles.
2. The arms occupy the entire distal border of the radials.
2. The posterior arms are dwarfed.
1. All the arms terminate in a growing tip.
1. All the arms are provided with ambulacral grooves.

Pinnules

1. Pinnules more or less sharply triangular in cross section.
1. All of the pinnules similar.
2. All of the proximal pinnules present.
1. Side- and covering-plates highly developed.
1. All of the pinnules provided with ambulacral grooves.

General

2. Skeleton composed of less than a million ossicles.

PLICATOCRINIDÆ

Calyx

1. Calyx in the form of a cup, protecting the visceral mass dorsally and laterally.
1. Basals present.
    1. Five basals (minority).
    2. Three basals (majority).
    1. Basals separate (majority).
    2. Basals fused into a single calcareous element (minority).
2. No infrabasals.
1. Five radials.
2. Interradials absent.
2. Anal *x* absent.
1. Interbrachials present.

Column

1. Entire column present.
1. Column jointed.
1. Column composed of short cylindrical columnals with radial crenellæ.
1. Column composed of a single type of columnals, without a proximale or nodals.
1. Column terminating in an expanded terminal stem plate.
2. Radicular cirri absent.
1. Cirri absent.

Disk

1. Disk entirely covered with plates.
1. Orals present.
1. Orals of different sizes.
    2. Orals a spherical triangle (minority).
    1. Orals with upturned inner edges (majority).
1. Mouth central.

Arms

    1. Arms composed of a linear series of ossicles, without IBr series (majority).
    2. Arms dividing one or more times, without IBr series (minority).
1. The first bifurcation is at a more or less indefinite distance from the second post-radial ossicle.
1. A suture between the first two post-radial ossicles.

1. Division series composed of an irregular number of ossicles.
1. The arms occupy only a portion of the distal border of the radials.
1. All the arms are of equal length.
1. All the arms terminate in a growing tip.
1. All the arms are provided with ambulacral grooves.

Pinnules

1. Pinnules more or less sharply triangular in cross section.
1. All of the pinnules similar.
1. Pinnulation of the arm bases more or less deficient.
1. Side- and covering-plates highly developed.
1. All of the pinnules provided with ambulacral grooves.

General

2. Skeleton composed of less than a million ossicles.

THE OCCURRENCE IN THE VARIOUS FAMILIES OF BOTH COMPONENTS OF CONTRASTING PAIRS

Excepting for the Holopodidæ, which is represented in the existing seas by only a single species, all of the families of recent crinoids agree in exhibiting, in closely related genera included in them, both of the contrasted characters in a greater or lesser number of pairs.

The number of entire pairs included in the various families is apparently proportionate to the known recent representation of each family. It is largest in the Pentacrinitidæ, which includes by far the greater part of all the existing types.

In detail the contrasted pairs in each family are as follows:

PENTACRINITIDÆ

I. *Calyx*

The presence or absence of basals.
The individual occurrence, or fusion, of the basals.
The presence or absence of infrabasals.
The occurrence of five or ten radials.
The presence or absence of interradials.
The presence or absence of anal *x*.
The presence or absence of interbrachials.

III. *Disk*

The presence or absence of plating on the disk.

The presence or absence of orals.

The condition of the orals, whether with or without upturned edges.

The central or excentric position of the mouth.

IV. *Arms*

The structure of the arms, whether a linear series of ossicles without IBr series, or dividing one or more times, or with IBr series.

The condition of the IBr_2, whether axillary or not.

The position of the first post-radial axillary, whether on the second post-radial plate or beyond.

The type of the union between the plates of the IBr series, whether a suture (pseudo-syzygy) or a synarthry.

The condition of the division series, including a definite or an indefinite number of plates.

The condition of the union between the radials and the arm bases, whether or not the latter occupy the entire distal border of the former.

The equality or inequality in the length of the arms.

The definite or indefinite termination of the arms.

The presence or absence of ambulacral grooves on all the arms.

V. *Pinnules*

The prismatic or cylindrical form of the pinnules.

The presence or absence of differentiation of the proximal pinnules.

The development or non-development of side- and covering-plates.

The presence or absence of ambulacral grooves on all the pinnules.

VI. *General*

The presence of more or less than a million skeletal elements.

PLICATOCRINIDÆ

I. *Calyx*

Five or fewer basals.

The individual occurrence, or fusion, of the basals.

III. *Disk*

The condition of the orals, whether with or without upturned edges.

IV. *Arms*

The structure of the arms, whether a linear series of ossicles without IBr series, or dividing one or more times, or with IBr series.

BOURGUETICRINIDÆ

I. *Calyx*

The individual occurrence, or fusion, of the basals.

IV. *Arms*

The condition of the IBr_2, whether axillary or not.

APIOCRINIDÆ

II. *Column*

The presence or absence of nodals.
The presence or absence of cirri.

PHRYNOCRINIDÆ

I. *Calyx*

The method of reduction of the calyx.

THE CRINOID FAMILIES CONSIDERED AS THE SUM OF THE CONTRASTED CHARACTERS EXHIBITED BY THEM

If we take each crinoid family, and, for each of the structural divisions given (Calyx, Column, Disk, Arms, Pinnules and General Structure), add the primitive characters (1) and the specialized characters (2), the difference between the two totals will give us an index of the relative condition of specialization of each of the different structural units.

The figures are as follows:

PENTACRINITIDÆ

Calyx	8 (1)	9 (2)	difference	1 (2)
Column	1 (1)	5 (2)	"	4 (2)
Disk	4 (1)	5 (2)	"	1 (2)
Arms	9 (1)	9 (2)	"	0
Pinnules	5 (1)	5 (2)	"	0
General	1 (1)	1 (2)	"	0
	28 (1)	34 (2)	difference	6 (2)

APIOCRINIDÆ

Calyx	4 (1)	5 (2)	difference 1 (2)
Column	5 (1)	4 (2)	" 1 (1)
Arms	4 (1)	5 (2)	" 1 (2)
Pinnules	4 (1)	1 (2)	" 3 (1)
General	0	1 (2)	" 1 (2)
	17 (1)	16 (2)	difference 1 (1)

PHRYNOCRINIDÆ

Calyx	5 (1)	5 (2)	difference 0
Column	4 (1)	3 (2)	" 1 (1)
Disk	1 (1)	2 (2)	" 1 (2)
Arms	6 (1)	2 (2)	" 4 (1)
Pinnules	4 (1)	1 (2)	" 3 (1)
General	0	1 (2)	" 1 (2)
	20 (1)	14 (2)	difference 6 (1)

BOURGUETICRINIDÆ

Calyx	5 (1)	6 (2)	difference 1 (2)
Column	4 (1)	3 (2)	" 1 (1)
Disk	1 (1)	2 (2)	" 1 (2)
Arms	3 (1)	5 (2)	" 2 (2)
Pinnules	5 (1)	0	" 5 (1)
General	0	1 (2)	" 1 (2)
	18 (1)	17 (2)	difference 1 (1)

HOLOPODIDÆ

Calyx	2 (1)	5 (2)	difference 3 (2)
Column	3 (1)	3 (2)	" 0
Disk	3 (1)	2 (2)	" 1 (1)
Arms	3 (1)	6 (2)	" 3 (2)
Pinnules	4 (1)	1 (2)	" 3 (1)
General	0	1 (2)	" 1 (2)
	15 (1)	18 (2)	difference 3 (2)

PLICATOCRINIDÆ

Calyx	6 (1)	5 (2)	difference 1 (1)
Column	6 (1)	1 (2)	" 5 (1)
Disk	5 (1)	1 (2)	" 4 (1)
Arms	8 (1)	1 (2)	" 7 (1)
Pinnules	5 (1)	0	" 5 (1)
General	0	1 (2)	" 1 (2)
	30 (1)	9 (2)	difference 21 (1)

In this connection the Pentacrinitidæ deserve more detailed examination. Very many characters are represented in this exceedingly large and very heterogeneous group by both components of the contrasted pairs, one of which is found in a—usually large—majority, while the other occurs in a—usually small—minority of the genera.

In the preceding lists the totals represent all of the characters under each heading; hence many characters in this family are given in the totals for both (1) and (2); such characters are neutral so far as their effect upon the general total is concerned.

If we eliminate this neutralization of one of the components of a pair by the other by considering only the components of each pair which are either represented alone or in the majority of the genera our results will naturally be somewhat different.

This method will give us the average state of specialization to which the family has attained, through eliminating the influence of a few conservative types which by the other method are accorded far more than their true phylogenetic importance.

	Total of all the characters	Total of the majority components, or the components singly represented, of each pair	Total of all the characters	Total of the majority components, or the components singly represented, of each pair		Total of all the characters	Total of the majority components, or the components singly represented, of each pair
Calyx	8 (1)	2 (1)	9 (2)	8 (2)	difference	1 (2)	6 (2)
Column	1 (1)	1 (1)	5 (2)	5 (2)	difference	4 (2)	4 (2)
Disk	4 (1)	1 (1)	5 (2)	4 (2)	difference	1 (2)	3 (2)
Arms	9 (1)	4 (1)	9 (2)	5 (2)	difference	0	1 (2)
Pinnules	5 (1)	2 (1)	5 (2)	3 (2)	difference	0	1 (2)
General	1 (1)	0	1 (2)	1 (2)	difference	0	1 (2)
	28 (1)	10 (1)	34 (2)	26 (2)	difference	6 (2)	16 (2)

THE TRUE PHYLOGENETIC SEQUENCE OF THE CRINOID FAMILIES HAVING RECENT REPRESENTATIVES

Judged on the basis of the preceding tables, the proper phylogenetic sequence of the crinoid families including recent species is as follows:

Pentacrinitidæ	28 (1)	[10 (1)]	34 (2)	[26 (2)]	difference	6 (2)	[16 (2)]
Holopodidæ	15 (1)		18 (2)		"	3 (2)	
Bourgueticrinidæ	18 (1)		17 (2)		"	1 (1)	
Apiocrinidæ	17 (1)		16 (2)		"	1 (1)	
Phrynocrinidæ	20 (1)		14 (2)		"	6 (1)	
Plicatocrinidæ	30 (1)		9 (2)		"	21 (1)	
	128 (1)	[110 (1)]	108 (2)	[100 (2)]	difference	20 (1)	[10 (1)]

According to the table just given the true phylogenetic arrangement of the families of recent crinoids, together with their relative positions in the scale of phylogenetic advancement, reckoning from the Plicatocrinidæ as the least specialized type, is as follows:

Pentacrinitidæ	+6	(+16)	or 30 (40)
Holopodidæ	+3		or 24
Bourgueticrinidæ	—1		or 20+
Apiocrinidæ	—1		or 20—
Phrynocrinidæ	—6		or 15
Plicatocrinidæ	—21		or 1

THE RELATIVE SPECIALIZATION OF EACH STRUCTURAL UNIT IN THE CRINOID FAMILIES INCLUDING RECENT SPECIES

In the various families the several structural units are not necessarily correlated in the amount of specialization they exhibit. The sequence in each family, as deduced from the preceding tables, is as follows, the most specialized structural unit being in each case placed at the head of the list, and units of equal value being bracketed.

Pentacrinitidæ	Apiocrinidæ	Phrynocrinidæ	Bourgueticrinidæ	Holopodidæ	Plicatocrinidæ
Column	{Calyx	Disk	Arms	Arms	General
Calyx	Arms}	General	Calyx	Calyx	Calyx
Disk	General	Calyx	Disk	General	Disk
{Arms	Column	Column	General	Column	Column
Pinnules	Pinnules	Pinnules	Column	Disk	Pinnules
General}	(No disk)	Arms	Pinnules	Pinnules	Arms

THE PHYLOGENETIC SEQUENCE OF THE RECENT CRINOIDS ON THE BASIS OF THE RELATIVE SPECIALIZATION OF EACH OF ITS COMPONENT STRUCTURAL UNITS

If we take each structural unit and in each family assign to it a number (from 1 to 6) according to its condition of specialization in reference to all the other families (if of the same value in two or more families giving it the same number in each), the family showing the lowest total will be the one which, as the sum total of all these structural units, is the most specialized.

The figures are given in the following table; the figure 1 indicates the maximum specialization for each structural unit, and the figure 6 the minimum.

	Calyx.	Column.	Disk.	Arms.	Pinnules.	General.	Total.
Holopodidæ	1	2	3	1	2	1	10
Pentacrinitidæ	2	1	1	4	1	2	11
Apiocrinidæ	4	3	0	3	2	1	13
Bourgueticrinidæ	3	4	2	2	3	1	15
Phrynocrinidæ	5	4	2	5	2	1	19
Plicatocrinidæ	6	5	4	6	3	1	25

If, however, we consider the Pentacrinitidæ on the basis of the average specialization, that is, if we consider each of the pairs of characters of which it exhibits both components on the basis of the majority representation alone, disregarding the small minority representation, this family easily takes precedence over the Holopodidæ.

EXAMINATION OF EACH OF THE STRUCTURAL UNITS IN DETAIL

A critical study of each structural unit, on the basis of the contrasted characters as previously given, is of considerable interest.

In the following tables each of these units is listed separately, the families in each case being arranged according to their relative specialization in regard to the unit under consideration, with the most specialized at the head of the list.

When the total is the same in two families, the one which possesses the higher number of specialized characters (or the lesser number of generalized characters) is given precedence. Families with identical totals are bracketed.

Calyx

1.	Holopodidæ	2 (1)	5 (2)	difference	3 (2)
2.	Pentacrinitidæ	8 (1)	9 (2)	"	1 (2)
3.	Bourgueticrinidæ	5 (1)	6 (2)	"	1 (2)
4.	Apiocrinidæ	4 (1)	5 (2)	"	1 (2)
5.	Phrynocrinidæ	5 (1)	5 (2)	"	0
6.	Plicatocrinidæ	6 (1)	5 (2)	"	1 (1)
		30 (1)	35 (2)	difference	5 (2)

Column

1.	Pentacrinitidæ	1 (1)	5 (2)	difference	4 (2)
2.	Holopodidæ	3 (1)	3 (2)	"	0
3.	Apiocrinidæ	5 (1)	4 (2)	"	1 (1)
4. {	Phrynocrinidæ	4 (1)	3 (2)	"	1 (1)
	Bourgueticrinidæ	4 (1)	3 (2)	"	1 (1)
5.	Plicatocrinidæ	6 (1)	1 (2)	"	5 (1)
		23 (1)	19 (2)	difference	4 (1)

Disk

1.	Pentacrinitidæ	4 (1)	5 (2)	difference	1 (2)
2.	Phrynocrinidæ	1 (1)	2 (2)	"	1 (2)
	Bourgueticrinidæ	1 (1)	2 (2)	"	1 (2)
3.	Holopodidæ	3 (1)	2 (2)	"	1 (1)
4.	Plicatocrinidæ	5 (1)	1 (2)	"	4 (1)
5.	Apiocrinidæ	.....	.....		.....
		14 (1)	12 (2)	difference	2 (1)

Arms

1.	Holopodidæ	3 (1)	6 (2)	difference	3 (2)
2.	Bourgueticrinidæ	3 (1)	5 (2)	"	2 (2)
3.	Apiocrinidæ	4 (1)	5 (2)	"	1 (2)
4.	Pentacrinitidæ	9 (1)	9 (2)	"	0
5.	Phrynocrinidæ	6 (1)	2 (2)	"	4 (1)
6.	Plicatocrinidæ	8 (1)	1 (2)	"	7 (1)
		33 (1)	28 (2)	difference	5 (1)

Pinnules

1.	Pentacrinitidæ	5 (1)	5 (2)	difference	0
2.	Apiocrinidæ	4 (1)	1 (2)	"	3 (1)
	Phrynocrinidæ	4 (1)	1 (2)	"	3 (1)
	Holopodidæ	4 (1)	1 (2)	"	3 (1)
3.	Bourgueticrinidæ	5 (1)	0	"	5 (1)
	Plicatocrinidæ	5 (1)	0	"	5 (1)
		27 (1)	8 (2)	difference	19 (1)

General

1.	Apiocrinidæ	0	1 (2)	difference	1 (2)
	Phrynocrinidæ	0	1 (2)	"	1 (2)
	Bourgueticrinidæ	0	1 (2)	"	1 (2)
	Holopodidæ	0	1 (2)	"	1 (2)
	Plicatocrinidæ	0	1 (2)	"	1 (2)
2.	Pentacrinitidæ	1 (1)	1 (2)	"	0
		1 (1)	6 (2)	difference	5 (2)

As shown by the preceding tables, the relative condition of specialization of the various structural units is as follows:

General	1 (1)	6 (2)	difference	5 (2)
Calyx	30 (1)	35 (2)	"	5 (2)
Disk	14 (1)	12 (2)	"	2 (1)
Column	23 (1)	19 (2)	"	4 (1)
Arms	33 (1)	28 (2)	"	5 (1)
Pinnules	27 (1)	8 (2)	"	19 (1)
	128 (1)	108 (2)	difference	20 (1)

This, however, is not a strictly correct presentation of the case.

In dealing with the families we considered in each the same number of contrasted characters and, with a few exceptions, each pair was represented in each family, so that the totals were directly comparable.

But the number of the contrasted pairs considered in the various structural units varies very greatly, running from 1 to 10. As there are six families, the actual number of pairs and the actual number of characters for each structural unit is as follows:

Structural unit	Pairs of contrasted characters	Total number of pairs in all the families	Total number of characters considered
Calyx................	10	60	120
Arms................	9	54	108
Column..............	7	42	84
Disk................	5	30	60
Pinnules............	5	30	60
General Structure....	1	6	12

Thus in order to raise the figures for all the structural units in all the families to the same relative value it is necessary to multiply each by the following numbers:

Calyx	10 x 63 x 6—3780	Disk	5 x 126 x 6—3780
Arms	9 x 70 x 6—3780	Pinnules	5 x 126 x 6—3780
Column	7 x 90 x 6—3780	General	1 x 630 x 6—3780

Applying these multiples to the table (the figures of which already include the multiple 6) we have:

General	630 (1)	3780 (2)	difference	3150 (2)
Calyx	1890 (1)	2205 (2)	"	315 (2)
Disk	1764 (1)	1512 (2)	"	252 (1)
Arms	2310 (1)	1960 (2)	"	350 (1)
Column	2070 (1)	1710 (2)	"	360 (1)
Pinnules	3402 (1)	1008 (2)	"	2394 (1)

In terms of the least specialized structural unit (the pinnules) this gives us the following ratios of specialization:

	According to the first table		According to the second table	
General	+5	24	+3150	5544
Calyx	+5	24	+315	2709
Disk	—2	17	—252	2142
Arms	—5	14	—350	2044
Column	—4	15	—360	2034
Pinnules	—19	1	—2394	1

THE CORRECTED RELATIVE SEQUENCE OF THE RECENT CRINOIDS ON THE BASIS OF THE RELATIVE SPECIALIZATION OF EACH OF ITS COMPONENT STRUCTURAL UNITS

In order to appreciate correctly the phylogenetic sequence of the recent crinoids on the basis of the relative specialization of each of its component structural units, it is necessary to apply as a correction the foregoing figures, representing the relative state of the specialization of each structural unit in terms of the least specialized.

To do this we may make use of the table given on p. 63, modified so that the least specialized structural unit will be indicated by the number 1, and the most specialized by the number 6 (that is, with the figures reversed), multiplying each number by the relative value of the structural unit under consideration in terms of the pinnules.

Applying both sets of figures given above, we get the following tables:

Applying the figures of the first table:

	Calyx	Column	Disk	Arms	Pinnules	General	Total	Relative standing of the families, the Plicatocrinidæ being taken as 100
Holopodidæ	144	60	34	84	2	48	372	312
Pentacrinitidæ	120	75	68	42	3	24	332	279
Bourgueticrinidæ	96	30	51	70	1	48	296	248
Apiocrinidæ	72	45	0	56	2	48	223	187
Phrynocrinidæ	48	30	51	28	2	48	207	174
Plicatocrinidæ	24	15	17	14	1	48	119	100

Applying the figures of the second table:

	Calyx	Column	Disk	Arms	Pinnules	General	Total	Relative standing of the families, the Plicatocrinidæ being taken as 100
Holopodidæ	16254	8136	4284	12264	2	11088	52028	259
Pentacrinitidæ	13545	10170	8568	6132	3	5544	43962	219
Bourgueticrinidæ	10836	4068	6426	10220	1	11088	42639	213
Apiocrinidæ	8127	6102	0	8176	2	11088	33495	167
Phrynocrinidæ	5418	4068	6426	4088	2	11088	31090	155
Plicatocrinidæ	2709	2034	2142	2044	1	11088	20018	100

The figures upon which these tables are based are:

Holopodidæ	6	4	2	6	2	2	22
Pentacrinitidæ	5	5	4	3	3	1	21
Apiocrinidæ	3	3	0	4	2	2	14
Bourgueticrinidæ	4	2	3	5	1	2	17
Phrynocrinidæ	2	2	3	2	2	2	13
Plicatocrinidæ	1	1	1	1	1	2	7

It will be seen that these corrected figures give the same sequence of families as the table summarizing the characters in each family (p. 60), except that the Holopodidæ come before the Pentacrinitidæ.

It differs from the sequence of the families on the basis of the uncorrected figures for the structural units in that the position of the Bourgueticrinidæ and the Apiocrinidæ is reversed.

If we judge the phylogenetic status of the Pentacrinitidæ on the basis of its average development, by considering only the character in each pair having the majority representation and leaving out of consideration the primitive features exhibited only by a negligible percentage of the species, the Pentacrinitidæ occupy a position well in advance of that of the Holopodidæ.

The Bourgueticrinidæ and the Apiocrinidæ undoubtedly are on very nearly the same plane, as is evident on even a superficial survey of their fossil species. Judging from the general structure of the recent genera the disk of the recent Apiocrinidæ, as yet not known, is probably more like that of the stalked pentacrinites than like that of the Bourgueticrinidæ or of the comatulids; if so, this would emphasize the phylogenetically advanced position of the Bourgueticrinidæ.

From the three tables showing the relative phylogenetic status of the crinoid families including recent species we get the following differences between each family and the family below it:

	From the table on p. 60	From the table on p. 64 (1st)	From the table on p. 64 (2nd)
Pentacrinitidæ	6	33	40
Holopodidæ	4	31	6
Bourgueticrinidæ	0	61	46
Apiocrinidæ	5	13	12
Phrynocrinidæ	14	74	55
Plicatocrinidæ	0	0	0

This indicates that there is a very broad phylogenetic gap between the Plicatocrinidæ (belonging to the Inadunata) and the remaining families (all of which belong to the Articulata). There is another broad gap between the Bourgueticrinidæ and the Apiocrinidæ.

Thus it would appear that the crinoid families represented in the recent seas, on the basis of their recent representation, fall into three well marked groups separated by broad phylogenetic gaps, as follows:

Group 1	Group 2	Group 3
Pentacrinitidæ Holopodidæ Bourgueticrinidæ	Apiocrinidæ Phrynocrinidæ	Plicatocrinidæ

THE RELATION BETWEEN PHYLOGENETIC DEVELOPMENT AND BATHYMETRICAL AND THERMAL DISTRIBUTION

The relationship of phylogenetic development to depth and to temperature presents a problem of considerable interest.

In the following table is given the amount of excess of the more primitive (1) or the more specialized (2) characters in each of the thirty-seven contrasted pairs.

Depth. Excess of		Temperature. Excess of		Depth. Excess of		Temperature. Excess of	
1	2	1	2	1	2	1	2
768	..	..	25.2	..	15	..	2.2
463	..	..	17.1	..	23	..	2.1
382	..	..	17.1	..	23	..	1.4
273	..	..	16.7	..	35	..	1.4
273	..	..	13.7	..	54	..	1.3
254	..	..	13.7	..	56	..	1.2
223	..	..	13.5	..	58	..	0.3
207	..	..	12.8	..	72	0.5	..
189	..	..	12.6	..	84	*0.5	..
156	..	..	8.0	..	84	1.5	..
107	..	..	7.2	..	135	2.1	..
72	..	..	5.9	..	156	2.1	..
48	..	..	5.1	..	156	3.0	..
41	..	..	5.0	..	187	7.2	..
23	..	..	3.8	..	212	7.5	..
23	..	..	*3.3	..	240	*8.3	..
16	..	..	2.5	..	254	9.8	..
6	..	..	2.5	..	255	13.7	..
..	3	..	2.5	..	..	..	..

In the temperature column the three figures marked with an asterisk (*) represent the difference between two sharply marked nodes in a single character pair.

These double nodes all fall under the more primitive characters (1). The difference between each element of the three double nodes and the average under the more specialized characters (2) are:

1	2
12.1	15.4
14.0	13.5
20.9	12.6

In the bathymetric distribution the more primitive components of the character pairs exceed the more specialized in 18 cases, while the reverse is true in 19 cases.

In the thermal distribution the more specialized components of the character pairs exceed the more primitive in 26 cases, the reverse being true in 11 cases.

The excess in depth of the primitive characters over that of the specialized is 1422 fathoms, each of the 18 primitive characters having an average depth of 196 fathoms, as against 110 fathoms for each of the 19 specialized characters.

The excess in temperature of the specialized characters over that of the primitive is 141.9°, each of the 26 specialized characters having an average temperature of 7.6°, as against 5.1° for each of the 11 primitive characters.

Thus it appears that, taken collectively, the specialized characters are developed in shallower and warmer water than the more primitive.

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A MAGNETON THEORY OF THE STRUCTURE OF THE ATOM

(WITH TWO PLATES)

BY
A. L. PARSON

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CONTENTS

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PART I. INTRODUCTORY

§1. General Remarks

The non-electrical bond between atoms, such as may be supposed to exist in the Hydrogen molecule, is an important factor in chemical union; but no plausible suggestion as to its nature has ever been made, and the failure to account for this bond is one of the greatest defects of the electronic theory of matter as it now stands.

Now the present theory is the outcome of an attempt made some years ago to remedy this defect even at the expense of a considerable departure from accepted fundamental ideas: it seemed then to the author that the idea of replacing the classical electron by the magneton here described, which makes the bond in question magnetic, was less revolutionary than any other that could definitely attain the end in view; and the contents of this paper bear witness to its subsequent fertility.

In postulating this magneton for chemical reasons, the phenomena of magnetism and radiation were of course not lost sight of. In the field of magnetism, the magneton has been at once and automatically as strikingly successful as in chemistry—as indeed we ought to require it to be. As regards its application to the phenomena of radiation, not much can be said at present; but the magneton seems *à priori* a promising conception here, and its possibilities have been looked into already by Dr. D. L. Webster in a paper on "Planck's Radiation Formula and the Classical Electrodynamics" (Amer. Acad., Jan., 1915).

As might be expected of a theory that had such an origin, the special considerations which led to the theory of Rutherford and Bohr, for example, were not taken into account; and thus any representation that it has been or will be able to give of the phenomena of α-particle scattering, of spectrum series, of the Röntgen ray spectra, or of the mass of the atom, are necessarily of a supplementary nature: but the theory does not, I believe, exclude the possibility of such representation for any of these phenomena (see the note in §16).

The properties of atoms fall into two distinct classes, the nature of this distinction having been clearly defined by J. J. Thomson, who points out that the atom behaves as if it were made up of a few electrons in an "outer shell" which are responsible for the chemical and light-absorbing properties of the atoms, surrounding a dense central mass made up of other electrons and positive electricity which might be called the "core" of the atom and is the seat of the strictly additive properties such as the mass, the Röntgen ray

emission, and the radioactivity: in the properties of the outer shell there is a periodicity, in those of the core not. To this brief sketch might be added the magnetic properties as obviously being due to the behavior of the outer part of the atom.

Now there is no theory that is able to explain, to any appreciable extent, both sets of phenomena. Nor even is there any that shows much promise in connection with the properties of the outer shell alone—especially the chemical and magnetic properties of the atom: most of the recent work (by Rutherford, Moseley, and others) has emphasized the other part of the problem—the properties of the core, or nucleus of the atom. Bohr's theory, based upon the conception of the nuclear positive charge, gives an interesting treatment of the problem of spectrum series, but its chemical application is very meager indeed (see §8). On the other hand, the present theory, since it originated in a study of the simpler aspects of chemical affinity, emphasizes the properties of the outer shell, though not necessarily at the expense of the other set of properties.

The essential assumption of this theory is that the electron is itself magnetic, having in addition to its negative charge the properties of a current circuit whose radius (finally estimated to be 1.5×10^{-9} cm.: see §16) is less than that of the atom but of the same order of magnitude. Hence it will usually be spoken of as the *magneton*. It may be pictured by supposing that the unit negative charge is distributed continuously around a ring which rotates on its axis (with a peripheral velocity of the order of that of light: §§5, 6); and presumably the ring is exceedingly thin. It might at first sight be supposed that if the electron were really thus magnetic, this property would have been detected in the behavior of kathode rays, but it will be shown later (§18) why it could not.

This rotation of a ring-shaped negative charge is intended to replace the usual conception of rotating rings of electrons in providing that orbital motion of electricity which is required by all theories of the magnetic and optical properties of atoms. No attempt will be made, however, to discuss the internal structure of the magneton.

With regard to the positive part of the atom, it will be necessary to avoid Rutherford's conception of a nucleus of very small dimensions—while fully recognizing the value of the evidence upon which he bases it—because it could not allow magnetons to take up the configurations that are essential to this theory, while the uniformly charged sphere of the Kelvin or Thomson "atom" is particularly

well adapted to the purpose. As for the possible intersection of positive spheres, since any great amount of intersection, or coalescence, of the model atoms of this or of any other theory must abolish their individuality, and since the positive sphere is little more than a simple mathematical expression of the coherence and individuality of the atom (see also §7), it is consistent, as well as very necessary, to assume that positive spheres cannot intersect. It will also be assumed that the volume of the positive sphere is normally proportional to its charge, that is, to the number of magnetons in the atom, but that it is compressible; and that the normal radius of the magneton is about half that of the positive sphere of the Hydrogen atom:[1] that the volume of the positive sphere of an atom is usually very different from the total space occupied by the atom, and a way to account for this, will be made clear later (§15).

Some reasons for believing that the electron is this magneton may be enumerated now, and discussed more fully afterwards. They are:

1. It seems to be the only satisfactory way of securing valence electrons which are at rest, or vibrating within narrow limits, near the surface of the atom—a great desideratum from a stereochemical standpoint—without abandoning the very essential idea of orbital motion in the atom.

2. Even if the orbital motion is abandoned, and we suppose that the atom does contain electrons of the usual type in positions of equilibrium near its surface, the purely electrostatic nature of their action would be altogether inadequate from a chemical point of view. The additional magnetic forces furnished by the magneton are exactly what the phenomena of chemical action require.

3. It alone can give the atom a structure that accords closely with what is known about the magnetic properties of matter.

A general discussion of these points is given in §§2, 3, 4, the last being considered first. In §5 there is a brief study of the forces between two magnetons. In §6 it is argued that a number of magnetons within a sphere of uniform positive electrification must *tend* to arrange themselves in groups of eight. This suggests structures for the atoms (§7) that are in good accord with the general relations in the Periodic Scheme. A model which partially illustrates the behavior of the group of eight magnetons is also described, and the accompanying plates (1 and 2) show photographs of it. In §8 these results are compared with what is known about the number of

[1] The diagrams in this paper are drawn to scale on this basis.

electrons in the atom, especially in reference to the hypothesis of atomic numbers, with which they conflict to a certain extent. Then follows a detailed application of the theory to the problems of valence (§§9, 10, 12, 13), with a discussion of the residual magnetic and electric forces due to different groupings of magnetons (§11). §§14, 15 deal with the volumes of atoms, and after this (§16) it is convenient to recapitulate the assumptions of the theory, which is at that stage fully developed. §§17, 18 deal with the moment of the magneton and a few questions connected with it; and §§19-23 contain a full treatment of magnetic phenomena.

§2. Considerations of Magnetism

The arguments for the substitution of the conception of the magneton for that of the classical electron in orbital motion, in explaining magnetic phenomena especially, are principally concerned with the radiation difficulties involved in the latter conception, although conclusive arguments of another kind (pp. 9, 10) are also available. The radiation difficulties have of course been a matter of common knowledge, but since on account of the apparent impossibility of avoiding them they have largely been ignored, it is worth while to make a critical study of them as they occur in applications of the electron theory to magnetism.

Of all the theories so far suggested, the present magneton theory is the only one that allows the existence of orbital motion and so of steady magnetic forces in the atom without the accompaniment of radiation processes. Disturbances or irregularities of any kind in the rotation of the magneton's annular charge will give rise to radiations certainly, but these will be non-essential to the chemical and magnetic individuality of the atom, and will be set up always by chance external stimuli, just as all the radiation processes in atoms (not including the emission of α and β "rays") are known to be in actual fact.

The contrary is the case with the classical electron. Every system of such electrons that has as yet been devised to explain magnetic phenomena either permits of continuous radiation or precludes the possibility of the atom giving radiations of at all the same kind as are observed: this will be made clear in what follows.

To begin with, it has long ago been pointed out by Sir J. J. Thomson that it is out of the question to consider orbits containing

only one classical electron, or a very few such, for these would radiate energy excessively fast.[1]

In a paper on "The Magnetic Properties of Systems of Corpuscles describing Circular Orbits" (Phil. Mag., 6, 673, 1903) he shows, however, that when the number in an orbit is as great as six and their linear velocity is small compared with that of light, the loss of energy becomes quite slow; and therefore he attempts to explain magnetic phenomena by means of rings of many corpuscles (electrons).

Now there are two great objections to such an explanation. In the first place, subsequent work by Barkla and others has shown that the lighter atoms, such as those of Hydrogen, Helium, Lithium, do not contain enough electrons to form even one such ring. It may be argued here that perhaps this evidence does not cover the total electron content of the atom. But at least it indicates that a certain number of electrons, distinct from the rest (if any), cannot be in orbital motion: and it is important to notice that these are the more loosely bound electrons, which play a part in chemical, magnetic, and optical phenomena.

The second objection originates in the fact that for diamagnetic atoms it is necessary to assume the existence of independent orbits in the atom that are so great in number or else undergo such rapid variations that they can be considered to have their axes uniformly distributed in three dimensions—this to account for a zero resultant magnetic moment. Now separate rings of this sort cannot maintain their individualities unless the difference in their radii is so great that their disturbance of one another is inappreciable. This condition, if granted, would limit the possible number of rings and the

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[1] Thomson has more recently proposed an electron with such properties that it could rotate in an orbit by itself. This is the electron with all its field concentrated along a narrow cone, or, to adopt Faraday's mechanism, with a single tube of force. Although he has not attempted to develop a theory of the structure of the atom from this, or to explain radiation or magnetism by it, he has used the conception in a theory of chemical affinity (Phil. Mag., May, 1914), though in a manner that is not at all definite, as may easily be imagined from the following considerations. Since the electron is attached to its equivalent positive charge by means of its single tube of force, it cannot exert any electric force upon any other body, and, even if it is in stable orbital motion, it cannot for the same reason give rise to magnetic forces or any sort of radiation. Hence, unless we accept some entirely new and at present inconceivable view of the properties of the electromagnetic field, such an electron is a wholly unprofitable conception. The assumptions made in Bohr's theory involve similar difficulties, which, however, are ignored in its development.

chance of their resultant moment being zero altogether too much, for most substances are diamagnetic; while if the radii are not different enough to prevent interference, an altogether chaotic motion will result in the atom. Hence rotating rings of electrons, where they can exist at all, must be coaxial, and all atoms containing them must have a magnetic axis. Now the diamagnetism of a substance does not of course extend to its constituent atoms in all cases, for stable molecules of no magnetic moment can be formed from magnetic atoms; but the diamagnetism of Helium and Argon gases (P. Tanzler, Ann. der Phys., 24, 931-938, 1907) must mean that the separate atoms of these elements are diamagnetic. Here it might perhaps be argued that rotating rings of electrons would have a gyroscopic action which, for perfectly independent atoms, would prevent a paramagnetic reaction. But this independence, which cannot be complete even in the gaseous state, must be lost in the liquid state, and yet there is no reason to believe that liquid Argon is paramagnetic (as far as can be ascertained, there have been no studied observations on the point); nor can the diamagnetism here be explained by the formation of polyatomic molecules. Also it should be observed that in oxygen and nitric oxide we have cases of paramagnetic gases.

Thus the idea of rings of electrons, which is used in the model atoms of Thomson, Rutherford, and Bohr, is experimentally shown to be untenable.

If the laws of electrodynamics are to be applied quite rigorously—and the present attempt to show that the magneton is fundamentally a better assumption than the classical electron in orbital motion of course requires this test—it may be said of a system of classical electrons that the separate electrons must either be at rest relatively to one another or else be in chaotic motion: in either case there may or may not be an additional rotation of the whole system about some axis passing through the center of the system. Now these conditions do not allow of a state such as was assumed in Thomson's theory of magnetism, as we have just seen, nor of a state such as was assumed in Langevin's theory, which we now come to consider.

Langevin (Ann. de Chim. et de Phys., 5, 70-127, 1905) assumes that the electrons rotate in individual orbits with radii not much smaller than that of the atom, thus producing average effects similar to those of ordinary current circuits; and that the axes of these orbits may be distributed in all directions.

But, as we have just seen, the mutual interference of these orbits, even if they each contained several electrons, would make their individual persistence impossible, and so the system would at once drift into chaotic motion. Let us therefore consider what modifications the supposition that there is this chaotic motion in the atom would make in Langevin's results.

It would not affect that part of the superstructure of his theory which deals with the orbits altogether statistically, for chaotic motion, from a statistical standpoint, is certainly equivalent to motion in a great many separate orbits whose axes are uniformly distributed in three dimensions. But for those parts of his work which deal with the Zeeman effect, or presuppose in any way the existence of separate definite periods of vibration in the atom, as, for example, where he says that the constancy of wave-lengths of spectrum lines shows that the interior of the atom is not much affected by temperature changes—for those parts, the assumption of motion in separate orbits is essential, and those parts would therefore have to be abandoned.

Again, in the case of either supposition, while the difficulty about accelerated motion of classical electrons being accompanied by continual radiation may be obviated by supposing that the atom contains so large a number of electrons that the compensation among their chance motions reduces the average radiation to an inappreciable amount, we still have the difficulty that for these compensations to be even approximately complete the number of electrons would have to be much greater than the number actually believed to be present in many atoms: this difficulty is thus similar to one that Thomson's theory encounters. Apart from this difficulty of the allowable number of electrons, the theory labors under the following dilemma: If the internal compensation is not complete, the radiation will be continual and promiscuous and will rapidly exhaust the atom's store of energy: if the compensation is complete, it does not seem possible to imagine any additional mechanism in such an atom that could explain the phenomena of radiation. We may notice also in passing that chaotic motion seems to be quite inadmissible from a chemical standpoint.

But in spite of the existence of such substantial objections to his fundamental assumption, even when it is replaced by the less objectionable one of chaotic motion, the superstructure of Langevin's theory is in excellent accord with the facts. The circumstance, then, that the substitution of the magneton here described for Langevin's electron in orbital motion not only removes all of the difficulties just

mentioned, but leaves the superstructure of his theory almost intact, is a strong argument in favor of the magneton. That this substitution can be made will be made clear by a short quotation from the conclusion of his paper:

. . . . and we can form a simple and exact picture of all the facts of magnetism and of diamagnetism by imagining the individual currents produced by the electrons to be indeformable but movable circuits of no resistance and very great self-induction, to which all the ordinary laws of induction are applicable.

The substitution I have suggested has further advantages: it makes a great advance upon Langevin's theory, owing to the fact that, whereas the reaction of one of Langevin's orbits to its environment must vary with the phase of the motion of its electron, each magneton has the properties of an ordinary current circuit at every instant, and it is no longer necessary to think of the orbits statistically either in respect to their number or in respect to time. The importance of this difference is easily shown. I will first give another quotation from Langevin.

After showing that a single one of his orbits can have a moment as great as that of the oxygen or iron atom, he says (*loc. cit.*, p. 122):

Since the individual currents due to the other electrons present in the molecule neutralize one another just as in a purely diamagnetic body, it follows that, in magnetic molecules, one or more electrons are sharply separated from the rest and are alone responsible for the magnetic properties, while all the electrons co-operate to produce diamagnetism.

These are perhaps the very same electrons, situated in the outer part of the system forming the molecule, that play a part in chemical actions, where we know that electrons equal in number to the valence come into action. That would account for the profound influence of the state of molecular association, physical or chemical, upon paramagnetism, and its virtual lack of effect upon diamagnetism.

It is remarkable how completely the present theory, by means of the magnetic forces between magnetons, realizes in a quite definite manner the state of affairs here hinted at by Langevin.[1] It should be observed, however, that he does not specify that the chemical forces due to his electrons are magnetic in nature. This is very probably

[1] Langevin's deduction that the magnetism of the oxygen or iron atom must be due to a few sharply distinct orbits is perhaps not altogether valid on his theory: a rotation of the whole of an otherwise diamagnetic system of electrons, whether moving in individual orbits or in chaotic motion, could give the same result. It may also be pointed out that if the orbits containing the few valence electrons were distinct, as Langevin suggested, the radiation from them could not possibly be reduced to almost zero by compensations, on account of their small number.

because the magnetic forces set up by electrons moving in orbits with about one-hundredth the velocity of light, as his are, would be much too small to be of significance in interatomic actions. However, a still greater objection, to bring out which was the chief purpose of the above quotation, is that such systems, as it seems, would not attract but *repel* one another magnetically.

Suppose that two electrons are constrained to move in parallel orbits, and in the same sense. If they can move synchronously, keeping always on the same side of their orbits, they will attract one another magnetically; but it can be shown that this is not a stable configuration, at least for velocities small compared with that of light. For, since the electric repulsion between them is greater than the magnetic attraction, the resultant force between them is one of repulsion; and thus if by some chance one of them is slightly displaced relatively to the other, the action of the tangential component of the repulsion between them will increase the separation until they are on opposite sides of their orbits, in which positions they will repel one another magnetically, as well as electrically.

When, therefore, it is remembered that the whole of the explanation of chemical phenomena given by the present theory depends upon the possibility of magnetic attraction taking place between two magnetons, it is evident that the substitution of the magneton for Langevin's electronic orbit is imperative.

Thus the magneton not only provides in a simple way the orbital motion which must otherwise be secured by making inconsistent assumptions about the behavior of classical electrons, but, what is equally important, it supplies a foundation for a detailed explanation of specific interatomic attractions of all kinds by providing an orbit which is equivalent to a current circuit at every instant and not only as an average effect in time.

This theory was first worked out in connection with the phenomena of valence; and probably that was necessary, for chemical phenomena are, from their nature, very much more detailed and distinctive than magnetic phenomena; but the groupings of magnetons about to be discussed from a primarily chemical standpoint must also bear the test of criticism from a magnetic standpoint. This test I will apply in detail at the end of this paper, but enough will be said here to show why the atoms of the inert gases should be the most diamagnetic of all atoms—as they are. In the same place the empirical magneton of P. Weiss will be considered: that is not a mechanistic conception and so could not have been developed in connection with the topics dealt with here.

§3. Stereochemical Evidence

The rapid orbital motion of the valence electrons, together with the other electrons in the atom, which is a feature common and essential to most theories of atomic structure, makes it hard to see how these latter can ever furnish an extended explanation of chemical phenomena.

The difficulty here is twofold. In the first place, it is known that the action of a single electron is the predominating feature of any chemical bond that undergoes electrolytic dissociation; and the general regularities of the Periodic Scheme make it highly probable that the same is true of bonds that do not, such as those in hydrocarbon molecules; besides, there is a fine gradation between these two extreme types. This, together with the stereochemical evidence for a definite spatial arrangement of the groups attached to a Carbon or other atom, makes it very unlikely that the valence electrons can be taking part in the rapid orbital motion of a system of electrons in rings. It is indeed conceivable that in a molecule of the type XH_n, where all the bonds are ionizable, the nuclear X atom may take into its own system of rings the electrons it has extracted from the H atoms, while the positively charged H residues arrange themselves symmetrically around it; but this could not apply to the bonds in which no actual transfer of an electron takes place, such as those probably are which do not ionize or leave charged groups when broken. In such cases, at least, it appears that the electron associated with a unit of combining action must remain near the point of contact with the atom that is held by that action.

The second objection, and for the Thomson model this merges with the first, is that rings of electrons must usually all rotate about the same axis, so that the symmetrical action in three dimensions which seems to be a normal property of the atom could be exerted by the Thomson atom only in the limited electrostatic sense already described, and not at all by Rutherford's atom. Fully to appreciate this difficulty one need only turn to that point in Dr. Bohr's papers (*loc. cit.*) at which he comes to consider the "tetrahedral" Carbon atom. We see there that the theory comes to a complete halt when confronted with the problems of "Chemistry in Space." Nor is the tetrahedral Carbon atom an isolated problem: the asymmetric compounds of other elements, such as Nitrogen and Cobalt, are still further beyond the reach of such theories, not only in their present form, but, it would appear, in any conceivable state of development along the same lines.

It should be noted in this connection that Werner, some years ago, put forward a theory of stereochemical phenomena (described in his "Stereochemie," pp. 48-50, 224) which discarded the notion of directed action, and represented the atom as exerting a uniform attractive force in all directions, without specifying the nature of that force. It did not profess to have a physical basis of any sort, but was meant to be nothing more than a symbolical representation of the facts, being directed chiefly against the narrow mechanical views of the time, according to which the Carbon atom was an actual tetrahedron and so forth. It is true that all the stereochemical phenomena for which ultra-mechanical explanations were at one time favored, such as optical activity, "ethylene" isomerism, and the facts that gave rise to Baeyer's "Strain Theory," or Bischoff's "Dynamic Hypothesis," can be better pictured by using the conception of equilibrium between more diffuse forces; but a compromise seems desirable on account of the difficulty in imagining the exact nature of such forces. Apart from other objections, a force like that of gravitation is too promiscuous in its action, while no concrete scheme of electrically charged or electrically polarized atoms is flexible enough to be consistently followed out through the molecule of the average Carbon compound. "Werner's Theory," then, is not a theory of chemical action so much as a clear statement of the conditions with which such a theory must comply. It will be seen that the structures derived for the atoms in this paper permit that mobility of linkages, the recognition of which led to the proposal of Werner's theory, without giving up the idea of definite units of combining action.

If, then, the valence electrons are in positions of equilibrium near the surface of the atom, the other electrons cannot have any translational motion, for these two states cannot coexist in the same system, except in the special case where the stationary electrons lie on the axis about which the others rotate. Now any attempt to reconcile this result with the certainty that there is some kind of orbital motion of electric charges within the atom leads inevitably to the idea of the magneton.

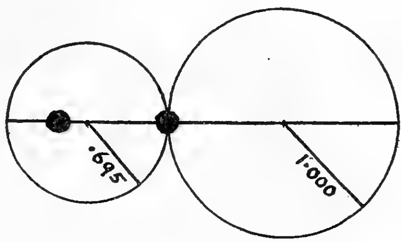
Again, theories involving rotating rings of electrons do not seem to provide a really satisfactory derivation of the valences of atoms. With them it is a question of how many electrons are stable in one ring; how many pass into another; and so on. Now, even if a limited agreement with the facts can sometimes be secured, the idea of rings of electrons cannot possibly harbor any essential peculiarity that could explain the definite system of "octaves" which is the

predominating feature of the Periodic Scheme. On the other hand, the magneton gives more or less independent units of valence, while the explanation to which it leads for the "Law of Octaves" is dependent ultimately upon the three-dimensional nature of space, and the fact that of the simple figures which are symmetrical in three dimensions the *cube* is alone in furnishing an arrangement of magnetons with a very low magnetic energy.

§4. The Scope of Electrostatic Theories of Valence

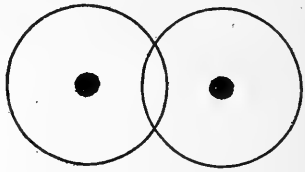
Since we have concluded that the atom cannot contain spherical or "point" electrons in rotating rings, let us next consider what are the possibilities of such electrons if they are supposed to be in a state of rest in the atom. It must be borne in mind that anything which is true for such electrons must also be a factor in the electrostatic part of the behavior of the magneton.

The fundamental problem from a chemical point of view is to show how two electrically neutral systems, such as atoms must be, can attract one another at all; and an analogy originally due to Lord Kelvin is typical of the way in which this question can be approached on the basis of the electrostatic action of movable charges. If a single electron is situated within a sphere of uniform positive electrification of equivalent amount, the whole is electrically neutral, but the force required to drag the electron out of its positive sphere is the greater the more dense the latter is, being inversely proportional to the square of its radius. If two such systems are brought into contact, the smaller and denser sphere will just be able to extract the electron from the other if the ratio of their radii is .695 : 1.000, as in the figure: now, if the two spheres are pulled apart, there will be an electrostatic attraction between them, and they will resemble the ions of a diatomic molecule like HCl. This principle holds true for all kinds of electrons, and will have to be taken into account in subsequent developments of the present theory wherever necessary (see §16), but its inadequacy as the sole basis of an explanation of chemical action is shown by the mere fact that it requires a higher atomic volume for Hydrogen than for any halogen element.



Attraction between neutral atoms might take place in another way.

If their positive spheres intersect, thus:



they will be attracted together. It can be shown, however, that in such a case there would be a tendency to complete coalescence (J. J. Thomson, "The Corpuscular Theory of Matter"); and the difficulties involved in such a possibility have already been emphasized in §1. Besides, an attraction of this sort could not explain valence.

Other suggestions of ways in which stationary valence electrons might account for attraction between neutral atoms have been made —mostly very tentative, and not physically definite enough to be criticised from the present point of view.

It is evident, then, that while the Kelvin model gives a rough representation of the HCl molecule, the cases of union between like atoms are a great difficulty from an electrostatic standpoint. The bond in the H_2 molecule is probably the simplest kind of combination between atoms, and yet it has proved to be the hardest of all to explain. Electrostatic explanations seem to be suited only to an alternate arrangement of the so-called "positive" and "negative" atoms. There is indeed a tendency to such an arrangement, even in organic molecules, aceto-acetic acid being a good example of this; and the tautomerism and acidic hydrogen atoms characteristic of such groupings are significant. But the assignment of positive and negative functions is not usually so easy: there is difficulty whenever groups of opposite nature are attached to the same Carbon atom, or groups of the same nature to contiguous Carbon atoms, as in the molecules

$$\begin{array}{cccccccccccc} + & & - & & + & & - & & & & & \\ H_3 & & O & & H_2 & & O & & & & & \\ ||| & & || & & || & & || & & & & & \\ C & - & C & - & C & - & C & - & O & - & H \\ - & & + & & - & & + & & - & & + \end{array}$$

$$\begin{array}{ccccccccc} H-C\equiv Cl_3, & & H_3\equiv C-C\equiv H_3, & & O=CH-CH=O. \\ ? \quad ? \quad - & & ? \quad ? \quad ? \quad ? & & - \quad ? \quad ? \quad - \end{array}$$

We are forced to the conclusion that there is a factor in the union of atoms which is unconnected with electrical polarization, and is almost as independent, simple, and ready to hand, as the stroke that is used in a structural formula to represent its action. This is provided by the magneton, which is eminently adapted to function as a "link," for its two sets of forces enable it to hold to its parent atom by

electrical attraction and to the magneton or magnetons of another atom by magnetic attraction at one and the same time.

PART II. THE STRUCTURE OF THE ATOM

§5. Forces between Magnetons

In assuming that the magneton has the properties of a current circuit (§1), we have pictured it as a rotating annular charge, and implied that the behavior of this charge is in accordance with the laws of ordinary electrodynamics. This picture I shall use in further delimiting the nature of the magneton as it is required by the present theory.

First must be considered the exact nature of the forces acting between two magnetons, and more especially the conditions under which they could be attracted together so closely as to coalesce; for coalescence, if spontaneous, would be an irreversible phenomenon, and therefore could not be possible for the magnetons that are concerned in the chemical actions of the atom. (We can, without inquiring into the nature of the magneton's structure, define coalescence as the coming of two magnetons into the most intimate contact.)

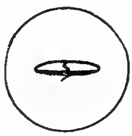
If two magnetons, of fixed dimensions and peripheral velocity, with their axes in the same straight line, are at a distance d apart, the forces between them obey the following laws:

The magnetic attraction or repulsion (M) is as $\frac{1}{d}$ when d is very small, and as $\frac{1}{d^4}$ when d is very great, compared with the radius of the magneton. The corresponding functions for the electrical repulsion (E) are $\frac{1}{d}$ and $\frac{1}{d^2}$. Thus, when d is small, as it would be just before coalescence, the forces are similar to those between two parallel linear charges of infinite length that are moving in the direcion of their length with a velocity equal to the peripheral velocity of the magneton (v). Then, if c is the velocity of light, the ratio of the forces, $\frac{M}{E}$, is equal to $\frac{v^2}{c^2}$. Therefore, if $v<c$, $M<E$ and magnetons cannot coalesce; also the resultant force is one of repulsion for all values of d, because M falls off more rapidly than E as d increases. Even with $v=c$, the ratio $\frac{M}{E}$ remains <1, except in its limiting value when d becomes zero: this would just permit coalescence, but only if the magnetons were first brought together by extraneous forces. I have neglected the " thickness " of the magneton: on account of this

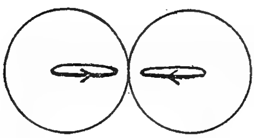
it would require a value of v somewhat greater than c for coalescence. (It should be said that the cases $v = c$ and $v > c$ do not here violate the law of relativity, for the continuous distribution of the charge around the magneton ensures it a uniform field for all values of v.)

Now it will be shown in §6 that if the magnetic forces between magnetons are to be great enough to account for chemical actions satisfactorily, v must not be much less than c. It is simplest, therefore, to assume v to be equal to c. We can neglect the mutual induction between magnetons approaching one another, as, for magnetons that are far from coalescing, these will be small; even if two coalesced, the flux per magneton would only be halved.

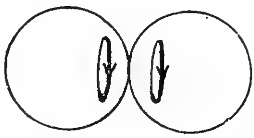
Turning now to the phenomena of chemical combination, we find that the bond in the H_2 molecule, which presents such difficulties to electrostatic theories, is the simplest of all to explain. It may be attributed to the magnetic attraction between two electrically neutral atoms containing one magneton apiece. Diagrammatically, the H atom may be represented:



; and the H_2 molecule:



or



. (These two configurations are equally satisfactory from a chemical point of view, but magnetically their properties would be very different.) The magnetons are pulled away from the centers of their positive spheres, and the fact that the H_2 molecule does not combine with more H atoms is accounted for by the obstructing action of the positive spheres, which prevent other magnetons from coming as close to these two magnetons as they are to one another. But residual magnetic forces remain, and would account, always for a part, and sometimes for almost the whole, of those actions between molecules and parts of molecules which are not indicated in structural formulæ and which find their most general expression in the phenomena of cohesion (§§11, 16). (For a calculation of the heat of dissociation of the H_2 molecule from this model, see §18.)

Before proceeding to the study of atoms containing more than one magneton, it may be well to point out that, although the fundamental concepts of this theory, the magneton and the positive sphere, are in

themselves simple, yet the situations to which they can give rise are so exceedingly complex from a mathematical standpoint, that a rigid quantitative treatment is practically impossible. In what follows, therefore, I have not usually attempted to arrive at much more than the relative order of the various effects. But even so, it seems possible to extend the theory over quite a wide range of facts before the uncertainties in its development accumulate enough to make its application meaningless.

§6. The Group of Eight

The configurations of small numbers of electrons at rest within a sphere of positive electrification have been described by Sir J. J. Thomson in his book, "The Corpuscular Theory of Matter," pp. 102-106, where he states that while three, four, and six electrons would take up triangular, tetrahedral, and octahedral arrangements respectively, the symmetrical cubical arrangement of eight can be shown to be unstable. The magneton, however, introduces two new factors into the problem: one, the extended ring shape of the electron, and another which is yet more significant, the "bi-polar" magnetic forces. To give a configuration with the minimum magnetic energy, it is evident that the currents in all adjoining parts of magnetons must be parallel and in the same direction, or, to take a cruder though possibly more vivid picture, the "N" and "S" poles of the magnetons must be placed alternately in every direction. From this point of view let us consider the groups of three, four, six, and eight magnetons (five and seven obviously have not the possibilities of the other numbers).

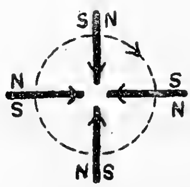
The stablest configuration for three magnetons is shown in the diagram 

. Four can have the configuration: 

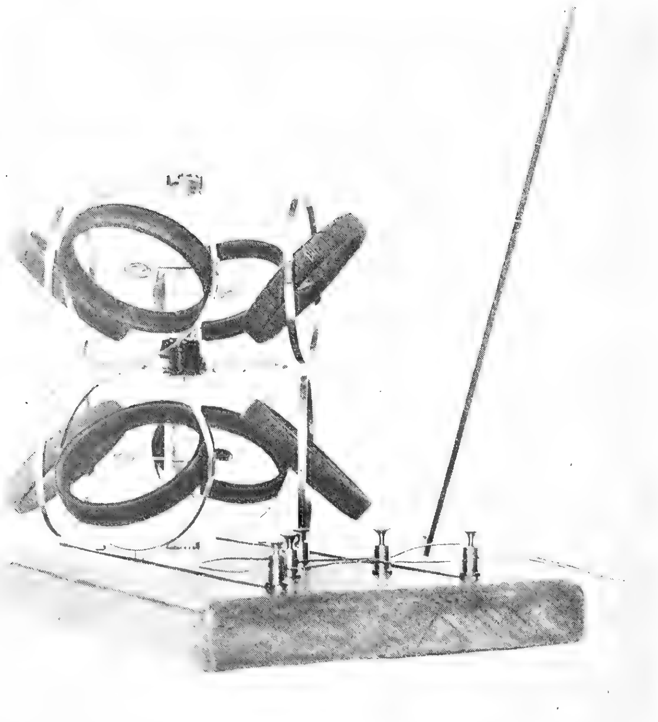
, which under symmetrical electrostatic conditions would form an irregular tetrahedron (this, which has been produced in a model, may be pictured by imagining one pair of opposite magnetons to be raised above the plane of the paper). The octahedral group of six would probably be made up in a similar way of three pairs of magnetons; but six can have a configuration of lower

magnetic energy than this, which, however, is not so symmetrical—this is a triangular-prism arrangement consisting of two parallel groups of three.

But quite apart from the lack of three-dimensional symmetry of some of these configurations (the effect of which will be seen shortly), they can none of them have so low a magnetic energy (in proportion to the number of magnetons) as the cubical arrangement of eight. This, with its three fourfold axes of symmetry, is magnetically ideal; and although it is not quite stable for spherical electrons, there is no doubt that it would be exceedingly stable for magnetons, because no other arrangement of eight can be nearly so symmetrical.

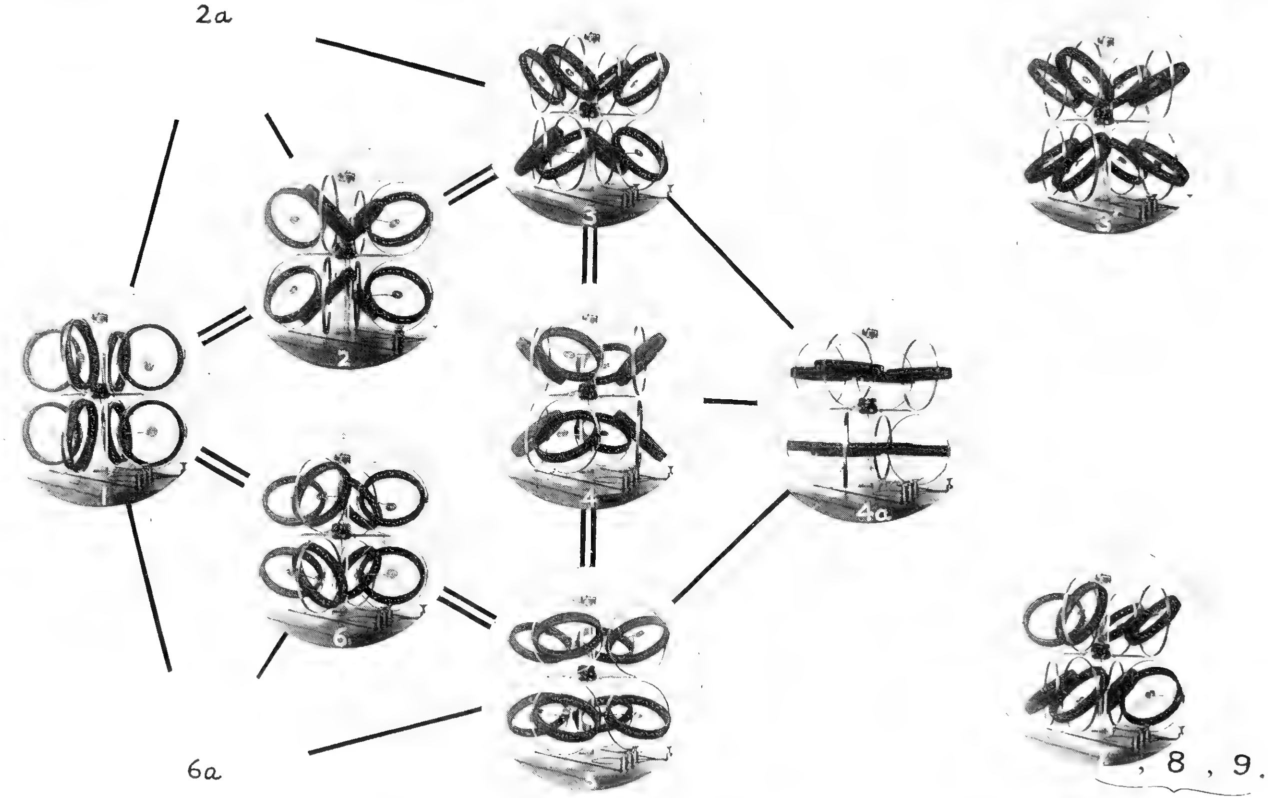
To illustrate the unique properties to be expected in this group of eight, I have made a model (plate 1) in which eight coils of insulated wire are set in gimbals at the corners of a cube, the side of which is two and a half times the radius of the coils. This cannot completely illustrate the behavior of the group, because the cubical arrangement is made compulsory, the distances are fixed, and the electric forces are absent; but, when excited by an electric current, it shows what configurations the eight can assume under such conditions. Most of these are shown on plate 2, where it may be seen that the most symmetrical and stable configurations resolve themselves into a cycle of six (figs. 1-6) which are very closely related to one another and easily interconvertible: 1, 3, and 5 are identical except for their relative attitudes in space, and the same is true of 2, 4, and 6. The group is thus very stable, and yet very mobile, for its magnetons can easily veer in all directions without destroying its identity. This mobility, which is not possible without three-dimensional symmetry, is a source of additional stability, for the group can adjust itself to casual external fields, such as it would continually meet with owing to the motion of the molecules, without needing to turn as a whole. The directions of the currents and of the flux in configuration 1 are shown in the following diagrammatic section of the upper four coils: 

. For the lower coils they are exactly reversed. The less symmetrical configuration numbered 7 is most easily described by saying that the four coils nearest to the camera have their "N" poles to the left, and the others have them to the



CONFIGURATIONS OF GROUP OF EIGHT

(See explanation Plate 2)



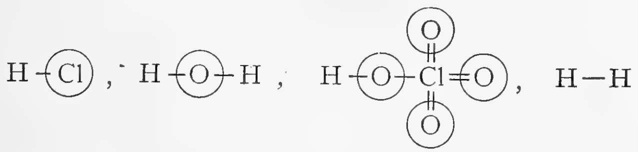
CONFIGURATIONS OF GROUP OF EIGHT

Note the effect of the earth's field, which lies in the direction shown by the line across Plate 1, in tilting the coils in config. 1; also in configs. 3 and 3′, which differ from one another only in the direction of the current in the coils.

right (or *vice versa*). All these configurations are free from magnetic moment; hence their presence in an atom would make for diamagnetism.

In its perfect symmetry, mobility, and very low magnetic energy, the group of eight evidently has a combination of properties which must make it more stable than groups of any number less than eight, or of any number not much greater than eight, as a consideration of the possibilities readily shows: it is reasonable, therefore, to suppose that this group will tend to be formed rather than other groups.

Further, the force retaining a magneton in a group of eight must be decidedly greater (*cet. par.*) than the force between two single magnetons—probably quite twice as great—and, if the magneton rotates with the velocity of light, would be great enough, in certain cases, to bring about the transfer of a magneton from one atom to another. We may then attribute to this effect that kind of combining action which is characteristic of electronegative atoms such as those of Oxygen or Chlorine. The former, as we shall see later, has six valence magnetons, and the latter seven, and each succeeds in making up a group of eight by extracting magnetons from other atoms. This state of affairs can conveniently be represented in structural formulæ by placing a circle around the symbol for every atom that is the seat of a group of eight thus formed, as follows:



The theory thus allows for the transfer of electrons in certain cases without requiring that it should be an inevitable accompaniment of chemical union (*cf.* the H—H molecule), and is in exact accord with the valence relations that are to be found in the short periods of the Periodic Scheme.

An atom containing exactly eight magnetons will neither extract magnetons from other atoms nor, under ordinary conditions, part with its own, and will have the properties of the Helium atom (*cf.* also its diamagnetism, §2). The photographs in plate 2 are thus a diagrammatic representation of the Helium atom, according to this theory.

§7. The Constitutions of the Atoms

The singular properties of the group of eight may possibly explain the sequence of the elements throughout the Periodic Scheme also. It is at once evident that a separation of all the magnetons in the

atom into groups of eight, with a remainder of valence magnetons, would give an ideal explanation of the "Law of Octaves." Indeed, no other arrangement of the magnetons—as, for example, in one large group—could give a picture of the facts, chemical and magnetic, that even approaches this in fidelity. What follows, therefore, is an attempt to analyze the behavior of large numbers of magnetons in a positive sphere with a view to finding conditions which could lead to such a grouping.

Any number of magnetons within a sphere of equivalent positive electrification must arrange themselves so as to secure an equilibrium between the two tendencies of the magnetic energy and the electric energy, respectively, to be at a minimum. The first would be satisfied by a gathering of all the magnetons into one very compact group, the second by an even distribution of single magnetons; and in view of the fact that magnetic forces increase more rapidly than electric forces as the distance diminishes, it might be thought that a likely compromise between the two tendencies would be the formation of groups containing the smallest number of magnetons that is compatible with a low magnetic energy, and at the same time with symmetry and mobility, in the group—that is, groups of eight. But more careful study of the matter shows that when a magneton is displaced from the position it would occupy in a plan of even distribution, the electrostatic forces of restitution are greater than the opposing magnetic forces; so that the stable condition is one of even distribution.

What has been said, however, implies the assumption that the positive sphere is rigid; if, on the contrary, it is compressible, we have a set of conditions that requires further consideration. This compressibility of the positive electricity will be found necessary to explain atomic volume relations and also the phenomena of gaseous collisions and α-particle scattering (see the note at the end of §16): it will therefore be introduced here.

The hypothetical positive sphere we are using must be supposed to possess two distinct sets of properties. In the first place it is a uniform charge of positive electricity, and on that account tends to expand indefinitely into space. Secondly, it has a coherence due to forces, something like elastic forces, which are in equilibrium with the expansive electrostatic forces. Thus when isolated from magnetons it would be in a state of distension, and very compressible. Further, to preserve the individualities of the positive spheres of different atoms we need to assume an internal structure like that of an elastic solid rather than that of a fluid. What has been said does not, as might seem at first, burden the positive sphere with more

complex assumptions than heretofore: it merely substitutes an elastic coherence for a rigid coherence, and it has the advantage of enriching the atom with additional degrees of freedom.

In such a sphere, each magneton will, by electrostatic attractions, condense positive electricity in and around itself, and thus its electrostatic action on other magnetons will be weakened: the first effect of endowing the positive sphere with elasticity will therefore be a general diminution in volume under the action of the electric and magnetic forces. In order that magnetons may not entirely neutralize themselves in this way, it must be further supposed that the elastic tension that obtains in the isolated positive sphere becomes zero when the charge density has increased to a certain value, and then changes sign, becoming a compression and combining with the electrostatic repulsion to oppose a further increase in charge density: such change of sign is of course connoted in the ordinary use of the term "elastic."

It is possible to make a somewhat elaborate study of the conditions in such an atom, but they are very complex and hard to discuss with any definiteness. Apart from the diminution of volume under the action of the electric and magnetic forces, the elastic sphere will apparently still behave, *under static conditions,* in much the same way as the rigid sphere; *i. e.,* there will probably be no spontaneous separation into groups. This statement is no more than a well-considered guess, because the complicated nature of the dependence of the repulsive forces in the elastic sphere upon the nature of the elasticity makes it very difficult to decide whether or not there can be conditions which would give us an unstable equilibrium in the case of even distribution. A spontaneous separation requires, of course, that at the point of even distribution the rate of change of the magnetic forces shall be greater than the rate of change of the combined electric and elastic forces as the magnetons move towards group formation.

There is, however, one important respect in which the two cases differ. Molecular collisions will cause much more irregular disturbances in an elastic than in a rigid sphere. Such disturbances will lead to the momentary formation of separate groups. Under these circumstances, the groups that form most often and have the longest average existence will be the smallest groups that can possess a minimum of magnetic energy and also great symmetry and mobility—the last being especially important under dynamic conditions. There is thus a strong probability of an average state of grouping into *eights* in the atom (see §6).

The effect just described is possibly sufficient in itself to determine the properties of an atom, although it would admittedly be more satisfactory to find a mechanism that could hold for a static condition of the atom also. If it should be found that the static separation is an essential idea, and that the elasticity of the positive sphere does not secure it, it would be better, I think, to make further and more arbitrary assumptions about the magneton or the positive part of the atom than to fall back upon the idea of a single large group of magnetons, because of the very much better picture of the facts that the grouping into eights affords us. One such set of assumptions has been suggested to me by Dr. D. L. Webster: the magneton might be supposed to exert magnetic forces that are greater than the electric forces at moderately short distances (as if v were greater than c); this would secure separation into groups, and the coalescence of such magnetons could be prevented by the assumption of a new repulsive force which followed an "inverse cube" law up to very short distances.

It must be remembered, of course, that a static condition of the atom cannot occur except at the absolute zero of temperature: furthermore, even if the distribution into groups of eight within an atom were statically stable, the reactivity of the valence magnetons could not be developed except under conditions of inter- and intra-atomic disturbance. On the other hand, if the grouping into eights owes its very existence to these disturbances, it is hard to see how the valence magnetons could retain, at any temperature, that marked individuality which is shown in the permanence of structure in organic molecules, and yet more in the stability of optical isomers—and which, indeed, was one of the original reasons for introducing the idea of this magneton (§§1, 3). However, we should expect, from the immediate point of view, to find just that relative stability of the "organic" compounds of Carbon, Silicon, and Titanium which is actually observed, because an increase in the number of groups of eight within the vibrating atom would more and more swamp the effect of the valence magnetons (in forming the "positive bond," at all events: see §9).

Without trying to settle this matter any more completely here, I will, for what follows, eke out the argument by the assumption that the separation into groups of eight actually can take place under static conditions—without, however, abandoning the dynamical conception of vibration and possibility of configurational changes within the atom, which is, as will be seen, the key-note of the treatment in this paper.

We can now derive constitutions for the atoms of all the elements in the manner shown in the accompanying table. Hydrogen, with one magneton only, is followed by a gap; then comes Helium with a group of eight (represented by " γ "), and the table goes on regularly with Lithium ($\gamma+1$), Beryllium ($\gamma+2$), Boron ($\gamma+3$), and so on. While this works out very well in the short periods, it is evident that for the long periods the plan must be modified; for Manganese ($3\gamma+7$) behaves very differently from Chlorine ($2\gamma+7$). Now a comparison of Vanadium with Phosphorus, Chromium with Sulphur, Manganese with Chlorine, and the Iron-Cobalt-Nickel trio with Argon, shows that these metals of the long period have just the properties that we should expect if there were no tendency in the systems represented by $3\gamma+5$, $3\gamma+6$, $3\gamma+7$ to form a fourth group of eight, and 4γ were really $3\gamma+8$. To represent this, I have placed a bar over the number referring to the valence magnetons, thus: $3\gamma+\overline{5}$, $3\gamma+\overline{6}$, $3\gamma+\overline{7}$, $3\gamma+\overline{8}$. This state of affairs, which accounts very well for the differences between what are usually called sub-groups A and B, is carried on, in a diminishing degree, through Copper, Zinc, and Gallium, with the constitutions $\begin{matrix}3\gamma+\overline{9}\\ \upharpoonleft\downharpoonright\\ (4\gamma+1)\end{matrix}$, $\begin{matrix}3\gamma+\overline{10}\\ \upharpoonleft\downharpoonright\\ 4\gamma+2\end{matrix}$, $\begin{matrix}(3\gamma+\overline{11})\\ \upharpoonleft\downharpoonright\\ 4\gamma+3\end{matrix}$, and the overdue group of eight is assumed not to be firmly established until Germanium ($4\gamma+4$) in group IV is reached. The constitutions assigned to these elements will be discussed in §13 of this paper.

I am unable to see any good reason for the non-formation of this group of eight, or to suggest any simple additional assumption that would secure it. It may be observed that each long period begins with an odd number of groups of eight already within the atom, but that is not likely to be of any particular significance. The non-formation, in certain cases, of the group of eight must then be classed as a subsidiary assumption (§§15, 16); but I have shown, in what follows, how well in accordance with the most various facts are the deductions that can be made from it. The tautomerism which has, as one result, been ascribed to the atoms of Copper, Zinc, and Gallium (and their analogues) seems to be a particularly fruitful conception (see §§13-15).

THE PERIODIC CLASSIFICATION OF THE ELEMENTS, WITH THEIR ATOMIC CONSTITUTIONS IN TERMS OF MAGNETONS

Trans.	?	He γ	Ne 2γ
I	H 1	Li $\gamma+1$	Na $2\gamma+1$
II	....	Be $\gamma+2$	Mg $2\gamma+2$
III	....	B $\gamma+3$	Al $2\gamma+3$
IV	...	C $\gamma+4$	Si $2\gamma+4$
V	....	N $\gamma+5$	P $2\gamma+5$
VI	....	O $\gamma+6$	S $2\gamma+6$
VII	....	F $\gamma+7$	Cl $2\gamma+7$

Long periods		Double long period		Long period
A 3γ	Kr 5γ	Xe 7γ	—+—	Nt 11γ
K $3\gamma+1$	Rb $5\gamma+1$	Cs $7\gamma+1$	—+—	——
Ca $3\gamma+2$	Sr $5\gamma+2$	Ba $7\gamma+2$	—+—	Ra $11\gamma+2$
Sc $3\gamma+3$	Y $5\gamma+3$	La $7\gamma+3$	—+—	——
Ti $3\gamma+4$	Zr $5\gamma+4$	Ce $7\gamma+4$	—+—	Th $11\gamma+4$
V $3\gamma+\overline{5}$	Nb $5\gamma+\overline{5}$	—+—	Ta $9\gamma+\overline{5}$	——
Cr $3\gamma+\overline{6}$	Mo $5\gamma+\overline{6}$	—+—	W $9\gamma+\overline{6}$	U $11\gamma+\overline{6}$
Mn $3\gamma+\overline{7}$	——	—+—	——	——
FeCoNi $3\gamma+\overline{8}$	RuRhPd $5\gamma+\overline{8}$	—+—	OsIrPt $9\gamma+\overline{8}$	——
Cu $3\gamma+\overline{9}$ $\downarrow\uparrow$ $(4\gamma+1)$	Ag $5\gamma+\overline{9}$ $\downarrow\uparrow$ $(6\gamma+1)$	—+—	Au $9\gamma+\overline{9}$ $\downarrow\uparrow$ $(10\gamma+1)$	
Zn $3\gamma+10$ $\downarrow\uparrow$ $4\gamma+2$	Cd $5\gamma+10$ $\downarrow\uparrow$ $6\gamma+2$	—+—	Hg $9\gamma+\overline{10}$ $\downarrow\uparrow$ $10\gamma+2$	
Ga $(3\gamma+\overline{11})$ $\downarrow\uparrow$ $4\gamma+3$	In $(5\gamma+\overline{11})$ $\downarrow\uparrow$ $6\gamma+3$	—+—	Tl $(9\gamma+\overline{11})$ $\downarrow\uparrow$ $10\gamma+3$	
Ge $4\gamma+4$	Sn $6\gamma+4$	—+—	Pb $10\gamma+4$	
As $4\gamma+5$	Sb $6\gamma+5$	—+—	Bi $10\gamma+5$	
Se $4\gamma+6$	Te $6\gamma+6$	—+—	——	
Br $4\gamma+7$	I $6\gamma+7$	—+—	——	

...., Proto-elements (see § 8).

——, Unknown elements the possibility of whose existence is not contested theoretically.

—+—, Rare-earth elements, possibly with the constitutions $7\gamma+\overline{5}, \ldots, 7\gamma+\overline{20}$ ($\not\doteq 8\gamma+\overline{12} \not\doteq 9\gamma+\overline{4}$). See § 13.

§8. The Number of Magnetons in the Atom

The following table gives a comparison of the numbers of magnetons apportioned to the atoms in the last section with the "atomic numbers" of van den Broëk (which are the numbers of electrons in the atom, according to Bohr), and also the atomic weights of the elements:

	H	He	Li	Be	B	C	N	O	F	Ne	Na...S..	Fe	Co	Ni..	Os	Ir	Pt	Au..
Magneton number (N)	1....	8	9	10	11	12	13	14	15	16	17...22...	32	32	32...	80	80	80	81...
Atomic number	1	2	3	4	5	6	7	8	9	10	11...16...	26	27	28...	78	79	80	81...
Atomic weight	1	4	7	9	11	12	14	16	19	20	23...32...	56	59	59..	191	193	195	197...

The two sets of numbers become identical for the heavy atoms for which Rutherford has calculated numbers of electrons from α-particle scattering, but for the lighter elements the atomic numbers seem at first to have much in their favor. First there is their close approximation to half the atomic weight, although this does not hold for Hydrogen or the heavy atoms. Secondly, the most definite calculations made from experimental results, viz., those from Barkla's work on the secondary Röntgen radiation (Phil. Mag., 5, 685-698, 1903; 21, 648-652, 1911), give numbers of electrons that are about half the atomic weight numbers for the lighter atoms.

The point to be emphasized here, however, is that none of such calculations have any meaning for the present theory, for the following reasons:

Rutherford's numbers, got from the phenomena of α-particle scattering, assume that the total charge on the electrons is equivalent to the charge on a small positive nucleus; but for the model atoms described in this paper, the nucleus, if there is any, must be neutral (see the note at the end of §16). Also the "characteristic numbers" got by Moseley, which, it should be remembered, are less than the atomic numbers by unity, have not been definitely correlated with the numbers of electrons in the atoms except through the idea of a positive nucleus. To turn to Barkla's work, the calculation of absolute values by means of Thomson's formula requires certain assumptions. One is that the dimensions of an electron are small compared with the length of a Röntgen ray pulse: this is not entirely the case with magnetons. Another, that the electrons in the atom are so far apart that any pulse can act on only one at a time: this can hardly be true of the electrons in the inner ring (radius 10^{-10} cm.) of the atoms of Bohr's theory, which is the prominent application of the hypothesis

of atomic numbers. Again, the values of e and $\frac{e}{m}$ used in the calculations are still subject to some uncertainty (an alteration in the accepted value of e from 1.13 to 1.55×10^{-20} has changed the number of electrons calculated for the average molecule of air from 25 to 14). And lastly, it has been shown by Crowther that a large part of the radiation scattered at the smaller angles is not accounted for by Thomson's formula, and Webster has pointed out that this is due to Thomson's neglect of a mutual reinforcement of the scattered radiations from the separate electrons. With so many uncertainties, the extant calculations from Barkla's results cannot have much exact significance for any theory of atomic structure.

The hypothesis of atomic numbers fails to accord with the chemical properties of the elements. J. W. Nicholson, in a recent criticism (Phil. Mag., 27, 541-564, 1914), has shown that Bohr's arguments about the behavior of electrons in his model atom are open to objection, and that the system with three electrons, for example, which Bohr assigned to Lithium, would actually behave like an inert atom. If applied to the present theory, the hypothesis would cause the same confusion. Nitrogen, with seven magnetons then in the atom, would be the most electronegative element known; Oxygen, with a single group of eight, would be inert; and Fluorine (then $\gamma + 1$) would be expected to behave like Lithium.

A circumstance frequently made mention of on behalf of this hypothesis is that the α-particle, which is a charged atom of Helium, always possesses exactly two units of charge. Now the sudden disappearance of the α-particle (as such) when its velocity falls below $.82 \times 10^9$ cm. per second can hardly be due to anything but its neutralization at this point. If at that still enormous velocity it can become neutral, one would not expect it to lose all its electrons at velocities that are not very much higher, and a theory like Rutherford's, or Bohr's modification of it, shows no reason why the two electrons, if there are only two, should not be lost one by one; whereas, if the neutral Helium atom is stable up to a velocity of $.82 \times 10^9$ cm. per second, the present theory would actually predict that for a considerable range of velocity above that point the atom would be stable with a deficit of two magnetons, partly because each succeeding magneton is harder to extract than the previous one, but mostly because the group of six which would remain comes much nearer to the group of eight in its magnetic stability than does the group of seven or any other small group (§6).

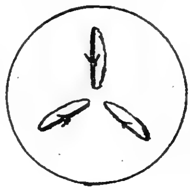
Lastly, the lack of any very definite evidence of the existence of atoms intermediate in mass between those of Hydrogen and Helium

is the main bulwark of the hypothesis of atomic numbers. According to the present theory, it must be remembered, there are missing from our observation on the earth's crust six theoretically possible elements, containing two to seven magnetons in the atom, which should occupy the gap between H (1) and He (γ). But it appears, on consideration, that even if such elements existed they would be inactive (with the exceptions mentioned below), because two to seven magnetons can form groups of much lower magnetic energy when alone in a positive sphere than in the presence of groups of eight, which must scatter them towards the surface of the atom.

The configuration inside the first two of these hypothetical atoms would be

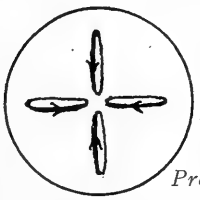
Proto-beryllium

and



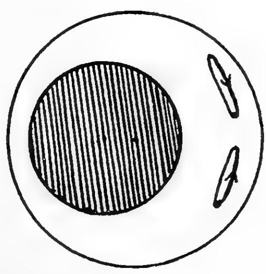
Proto-boron

, and in the third probably



Proto-carbon

, perhaps with the four magnetons at the corners of an irregular tetrahedron (see §6). The last two of these have no magnetic moment and therefore no attraction for other magnetons at a distance; also they could not unite stably with H atoms even when brought into contact, for the intra-atomic forces beween the magnetons are too strong to allow them to separate for such a purpose. The first atom, Proto-beryllium, has a moment, and it might combine with *one* H atom (for the two magnetons are too strongly attracted together to be able to act separately); but it would not be expected to part with a magneton to make up a group of eight in another atom—as the H atom does in H-Cl. The probable behavior of Proto-beryllium can be compared with that of Beryllium by considering the diagram for the atom of the latter. Thus the only kind of combination that seems possible for these proto-atoms is where a group of eight is made up within the atom itself. This would be impracticable except for atoms containing as many



as five magnetons already (§9), but Protofluorine (7), certainly, should be an even more strongly "negative" element than Fluorine $(\gamma+7)$.

As far as these atoms are inactive, or combine only with Hydrogen, their absence from the earth is to be expected, for they are light enough to escape from the atmosphere, as even Helium is believed to do slowly; but the absence (or excessive rarity) of Proto-oxygen and Proto-fluorine must be attributed to unknown causes of the same sort as condition the rarity of Neon, Krypton, and Xenon, and the apparent absence of the analogues of Manganese.

Strong evidence for the existence of the proto-atoms is the occurrence in the spectrum from the corona of the sun (where gravitation is much stronger than on the earth) of the bright unfamiliar line attributed to an unknown element, Coronium; on similar grounds an element Nebulium is believed to exist in the nebulæ. Such elements as these could apparently find no place in the Periodic Scheme except before Helium. (The proto-elements have been discussed, though from a different point of view, by J. W. Nicholson (Phil. Mag., 22, 864, 1911).)

A noteworthy feature of this magneton theory is that it leads to numerically identical constitutions for the atoms of the three elements in each of the triplets in the transition group (Fe, Co, Ni; Ru, Rh, Pd; Os, Ir, Pt). According to Moseley's calculations from the Röntgen ray spectra of the elements (Phil. Mag., 26, 1024-1034, 1913), the constant difference of one unit (presumably one electron) from atom to atom applies to these elements just as to the rest. There may indeed be some such regular difference in the nucleus, but we have seen above that Moseley's results cannot well mean anything for the "outer shells" of the model atoms of the present theory, and the way in which the physical and chemical properties of these elements throw them together in one group suggests strongly that there is in their case some less fundamental difference in the structure of that part of the atom.

PART III. VALENCE

§9. Two Kinds of Combining Action and Three Kinds of Bonds

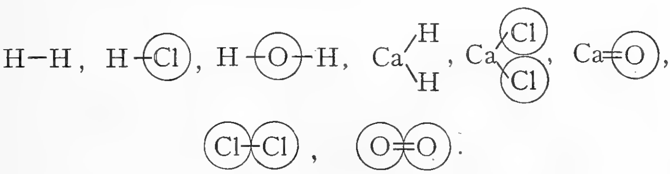
There is no simple term in general use for the "combining action" of an atom that is broad enough to include the ideas of a numerical factor (valence), an intensity factor (affinity?), and sign (in the conventional chemical sense), all within itself. I shall therefore frequently speak of the *action* of an atom, to include all this.

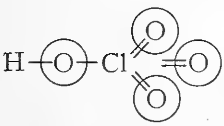
From the results in §§6, 7, we are able to distinguish between two distinct kinds of action for the atoms:

1. Where an atom combines with others through the magnetic forces due to its separate valence magnetons, no attempt being made to form a group of eight in the atom. This is characteristic of the atoms which have always been classed as "*positive,*" so the term does very well to describe this kind of action; but it must be made clear that in this sense its connection with positive electricity is only incidental (*e. g.*, when the H atom combines with a Cl atom it gives up its single magneton to the latter and is then left with a positive charge, but this does not happen when it combines with another H atom in H_2, or with a C atom in CH_4: see below).

2. *Negative* action, where an atom which possesses nearly eight valence magnetons succeeds in making up a group of eight by extracting magnetons from other atoms.

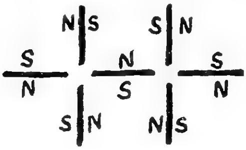
In the following typical molecules, Ca and H atoms display *positive* action, and O and Cl atoms *negative:*

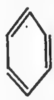
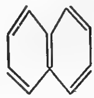


In  , however, Cl is acting positively.

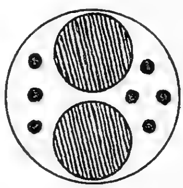
The way in which the Cl_2 and O_2 molecules have been represented requires explanation. In Cl_2 we have two atoms that contain seven valence magnetons each and are normally monovalent negatively. It is evidently impossible for them both to form groups of eight simultaneously, nor, on account of molecular collisions, would one be likely to form such a group permanently at the expense of the other: we are thus led to think that this group must oscillate between the two atoms. If this occurs, there must be formed, transitorily, a condensed group of fourteen magnetons, which is related to the group of eight very much as the naphthalene molecule is related to that of benzene. If we take a horizontal section through the upper four coils in config. 1 (see §6), we get the diagram . A similar

section through the condensed group of fourteen would give us:

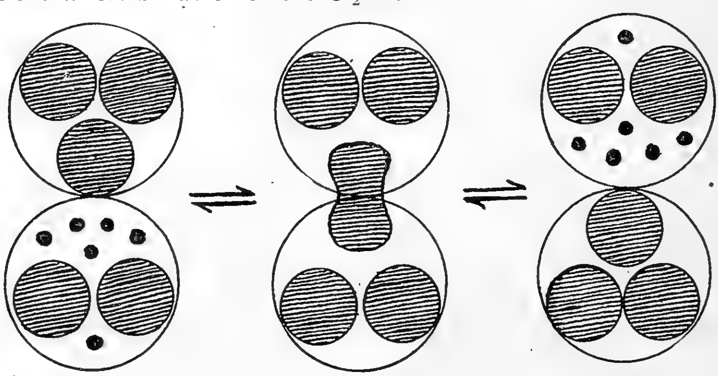


(*cf.*  and ). It may be seen from this that the group would have a certain degree of intrinsic stability, although not nearly so much as the more symmetrical and mobile group of eight. In the same way the O_2 molecule may contain a transitory group of twelve, which can be pictured by imagining config. 1 to have three coils in each vertical row instead of two: a condensed group of ten for the N_2 molecule is not so easy to imagine, but the same oscillation of the "negative" function can take place there: $\hat{N} \equiv N \rightleftharpoons N \equiv \hat{N}$ (where $\wedge$ represents a pair of free magnetons. A bond of this kind, which allows of the more or less rapid oscillation of the "negative" function (*i. e.,* of the group-of-eight formation) between two atoms, with the intermediate formation of a condensed group, will be called the *negative bond.*

Diagrammatically, then, the Cl atom may be represented:

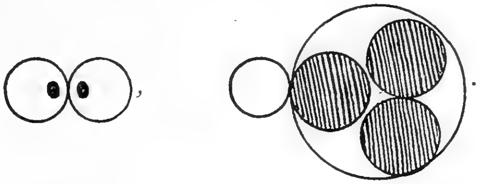
,

and the whole behavior of the Cl_2 molecule:



Since we have called the bond in Cl—Cl the *negative bond,* that in H—H may appropriately be called the *positive bond,* and

that in H—Cl the *neutral bond.*[1] Diagrammatically the molecules H—H and H—Cl may be represented:



[1] In the case of the *neutral bond,* this formal terminology becomes somewhat artificial, and possibly misleading—for it is exactly there that an electric polarity is developed in the molecule by the transfer of a magneton. On the other hand, this bond has closely associated with it the idea of the union of oppositely charged ions to give an electrically neutral molecule.

But in any case the choice of terminology here is difficult. Perhaps the best, from a descriptive point of view, is that given by Bray and Branch in a paper on "Valence and Tautomerism" (Journ. Amer. Chem. Soc., 35, 1440-1447, 1913). Their "polar bond" is largely identical with the *neutral bond* here. But it would not be possible to use their term "non-polar" to describe what is here called the *positive bond,* because the latter can probably be "polar" in a few cases (*e. g.,* in metallic hydrides: these are not discussed in this paper, but see §16; and the present purpose is to classify bonds by the mechanism of their formation rather than by their ultimate effect upon the behavior of the molecule. However, the use of the terms "polar" and "non-polar" in a purely adjectival sense, such as their authors meant, is highly desirable: the *negative bond* might then be described as "ambi-polar," as I have indicated below.

The following table of some possible terminologies seems to show that the most formal, besides giving a good synthesis of ideas, is perhaps the safest:

The action of an atom		The bond between atoms			Criticism
positive	negative	positive	neutral	negative	Formal.
extensive	intensive	....	....	....	Vaguely descriptive.
dispersed	collected	....	....	....	
....	....	non-polar (not always)	polar	ambi-polar	Describes electric effect.
....	....	linear	cubical	oscillating cubical	Describes arrangement of magnetons.
simple	compound	simple	compound	oscillating compound	Vague.
....	....	two-	eight-	oscillating eight-	Gives number of magnetons used.

With regard to these terminologies, objections besides those which I have mentioned will readily suggest themselves.

(The above diagrams are drawn on half the scale of those given in the previous sections. The black dots, representing valence magnetons, do not of course show their real distribution, whatever that may be.)

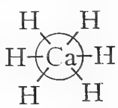
The exact use of the terms *positive, negative,* and *neutral,* in connection with this theory, in describing an atom's action on the one hand, and the bond between atoms on the other, is then as follows: A *positive*[1] atom+a *positive* atom use the *positive bond:* H—H.

A *negative* atom+a *negative* atom use the *negative bond:* (Cl—Cl).

A *positive* atom+a *negative* atom use the *neutral bond:* H—(Cl).

There follows a table of the typical oxides and hydroxides that are so familiar in connection with the Periodic Scheme, together with the numerical values, and relative intensities (qualitatively: see below), of the combining actions derived for the atoms in this paper:

Group:	0	I	II	III	IV	V	VI	VII
Highest normal oxide	....	Li_2O	BeO	B_2O_3	CO_2	N_2O_5	....	....
	....	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl_2O_7
Positive valence	0	1 >	2 >	3 >	4 >	5 >	6 >	7
Hydrides	....	LiH	(CaH_2)	BH_3	CH_4	NH_3	OH_2	FH
Negative valence	0[or 8 <	7 <	6 <	5] <	4 ? <	3 <	2 <	1
		impracticable						

It will readily be seen that this scheme, which is a direct mechanical consequence of the assumptions of this theory, contains all the features of the well-accredited scheme of "valencies and contravalencies" which is associated with Abegg's name; and it also shows why the "contravalencies" in groups I-III should be merely hypothetical—for example, the Ca atom, with only two valence magnetons, can be seen, from electrostatic considerations, to have very little or no tendency to draw in six more from six H atoms to give the molecule  : instead, it simply combines with two, using the positive bond: H—Ca—H.

For those atoms that do show negative action, it is to be expected that its intensity will diminish as the number of outside magnetons

[1] Or, better, "positively acting," and so for the rest.

required to make up the group of eight increases, because of the increasing electrostatic strain involved; and so the order of intensity is $\left.\begin{matrix} F \\ Cl \end{matrix}\right\} > \left.\begin{matrix} O \\ S \end{matrix}\right\} > \left.\begin{matrix} N \\ P \end{matrix}\right\} > \left.\begin{matrix} C \\ Si \end{matrix}\right\}$. If the intensity of the negative action of the atom of an element is to be judged by the readiness with which it unites with Hydrogen or with the metals, as is reasonable, Nitrogen and Phosphorus must be fairly weak in this respect, and Carbon and Silicon can have very little tendency to combine negatively; this is just as theory here would lead us to expect.

Further, this gradation in the tendency to form the group of eight leads us to the conclusion that there must be, in the molecules of the hydrides of these elements a kind of tautomerism or dynamical equilibrium between the two possible modes of union, as follows:

$$\begin{array}{ccccl} [C \equiv H_4] & (N \equiv H_3) & O = H_2 & F - H & \text{neutral bond (polar),} \\ \upharpoonleft\!\downharpoonright & \upharpoonleft\!\downharpoonright & \upharpoonleft\!\downharpoonright & \upharpoonleft\!\downharpoonright & \\ C \equiv H_4 & \hat{N} \equiv H_3 & (\hat{O} = H_2) & [\hat{F} - H] & \text{positive bond (non-polar),} \end{array}$$

the proportion of polarized molecules increasing regularly from CH_4, where it is very small, to HF, in which it greatly predominates. In view of the incessant vibrations of all molecules, this is mechanically a more likely condition than the statical one in which the Carbon atom just does not, and the Nitrogen atom just does, succeed in forming the group of eight. The constitutions of these molecules are of fundamental importance in chemistry, for they are the four typical molecules of the old type theory, and three of them, viz., NH_3, OH_2, and FH, typically represent almost all ionizing solvents; these three also differ from CH_4, as we have seen, in that the unpolarized tautomer contains a certain number (always even) of valence magnetons that are free—that is, it is unsaturated.

With regard to the intensity of the positive action of an atom (as shown in its typical oxide), the increasing number of magnetons that must be extracted from an atom in forming its typical oxide, as we pass from group I to group VII, results in a decreasing stability of that oxide, for electrostatic reasons. Hence we have the following stability relations:

$$\begin{array}{l} B_2O_3 > CO_2 > N_2O_5 > [OO_3] \quad [F_2O_7], \\ Al_2O_3 \quad SiO_2 > P_2O_5 > \ SO_3 > \ Cl_2O_7, \\ \qquad\qquad TiO_2 \quad V_2O_5 > CrO_3 > Mn_2O_7, \text{ etc.} \end{array}$$

The progress from basicity to acidity in the hydroxides as we pass from group I to group VII is a matter of the greatest interest, and much light can be thrown upon it by considering the electrostatic

forces set up by the extraction of different numbers of magnetons from the parent atom: I hope to discuss this in a somewhat quantitative way, when dealing with the "retaining powers" of atoms for magnetons (see §16).

In this section the relations between analogous atoms in any group of the Periodic Scheme have not been discussed: this also must be postponed.

§10. MOLECULES CONTAINING THE NEGATIVE BOND

The more typical compounds of the elements have been briefly classified in the last section: many compounds of less ordinary types may be brought into the general scheme by means of the negative bond. As in the case of Cl—Cl, this is formed between those atoms and groups only that are capable of negative action. Some such are: —Cl, —O—H, —N$<^{H}_{H}$ (which is for the most of the time in the other phase: see §9), —O— SO_2—O—H; and among their binary compounds we have:

Cl—Cl, chlorine molecule;

Cl—O—H, hypochlorous acid;

Cl—N$<^{H}_{H}$, chloramide;

H—O—O—H, hydrogen peroxide;

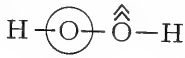
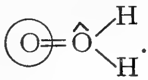
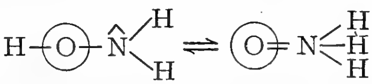
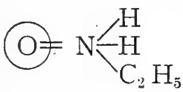
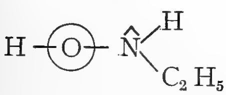
H—O—N$<^{H}_{H}$, hydroxylamine;

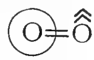
$^{H}_{H}>$N—N$<^{H}_{H}$, hydrazine;

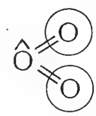
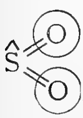
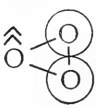
H—O—O— SO_2—O—H, monopersulphuric acid;

H—O— SO_2—O—O— SO_2—O—H, persulphuric acid.

Molecules like these are liable to the same kind of tautomerism as HCl, H_2O, H_3N molecules (§9), but it will be more complicated, for

either half can tautomerize. The constitution given to H_2O_2, for example, is only one phase in the oscillations of a very mobile molecule. The half-polar tautomer  might easily pass over into . This would be exactly analogous to the change  for hydroxylamine; and while there is no definite evidence that this takes place in the simple substance, it is known that the attempt to get an amine oxide like  always yields the β-hydroxylamine  (unless the amine is tertiary).

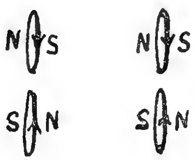
With regard to the "double" negative bond in the O_2 molecule, the unsaturated tautomer, which most likely predominates,  (§9), would account for that adding on of whole molecules which seems to be the first stage of oxidation by gaseous oxygen (*cf.* "autoxidation" phenomena).

Ozone, which is formed by the union of an O_2 molecule with a nascent O atom, may then, in different phases, be  (like : see §11), or  with the negative bond oscillating around the ring.

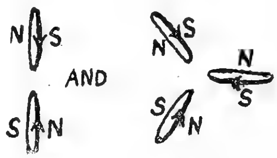
§11. Residual Forces, Magnetic and Electric

In discussing the actions between atoms in the foregoing pages, we have considered only the primary, or valence, effects of the magnetons, and have left out of account the residual magnetic forces that must be exerted to a greater or less extent by all combinations of magnetons. Now, as a rule, these forces would be negligible in determining the *number* of atoms in molecules such as are stable in

the gaseous state, because they are so much weaker than the primary forces; although this may not be so invariably, just as it is not true that the primary forces are always effective in holding together the parts of the molecule of a gas (*cf.* N_2O_4, or I_2). But the residual forces *within* a molecule might affect its properties considerably. These forces, as they are magnetic, will be forces of attraction wherever possible, and we can in many cases form a rough idea of their distribution, magnitude, and influence on the molecule.



Let us first consider the factors that would determine the amount of attraction between two magnetons. In the case of simple groups, such as groups of two each, it is evident that they must take up certain "complementary" attitudes towards one another, as shown in the figure, if there is to be any great amount of attraction between them, and such complementary attitudes are not possible unless the two groups are very similar in structure. For instance, the two groups



can attract each other when in the relative attitudes I have depicted, but not so much as the more symmetrical pair first mentioned.

This principle seems to be perfectly general; and, in applying it to the present theory, we can distinguish between two very distinct types of groups: (1) groups of eight, with their stable symmetrical distribution of magnetons; and (2) less symmetrical groupings, where the magnetons are "free" or in positive bonds (no doubt further distinctions could be made here).

The group of eight has a symmetrical but very checquered field, and is not fitted to attract a single magneton very strongly, or any group that is not very similar to itself. In the same way, less regular groups may under favorable circumstances have more attraction for one another than they could have for groups of eight.

Not the least important feature of these attractions is that the external field of a group of any kind of structure will tend to impose a similar structure upon any neighboring group, so as to increase the attraction between them and lower their mutual energy. This tendency will affect irregular groups more than groups of eight, for their magnetons are less firmly held, so that irregular groups will

more frequently be able to take up configurations such that they can attract one another. It must be remembered, of course, that, from the very nature of magnetic forces, no groups of magnetons could affect one another appreciably at distances that are much greater than the distances between the magnetons within the groups, for changes such as could decrease the mutual energy of the groups must, except for slight changes, increase their internal energy still more, because the distances there are smaller. However, intra-molecular distances would not usually be too great, for we have assumed the radius of the magneton to be of the same order of magnitude as that of the atom.

We have now reached the following generalizations about the mutual action of groups of magnetons:

1. Groups of eight can attract one another and irregular groups can attract one another much more than irregular groups can attract groups of eight.

2. A group of eight will tend to induce the formation of other such groups in its vicinity; and conversely, an irregular part of the molecule will tend to weaken any groups of eight that are near to it. Groups of eight will also mutually reinforce one another.

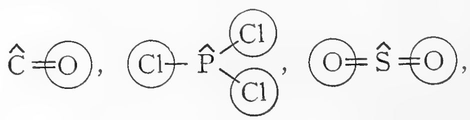
These principles are of great promise in connection with the influence of "negative" groups in the molecules of Carbon compounds, for the negative action of an atom has been identified, in the preceding pages, with its tendency to form a group of eight. Another application is to the properties of unsaturated molecules (§§12, 13), for these will naturally show the disturbing influence of free magnetons on groups of eight, if the present conclusions are correct.

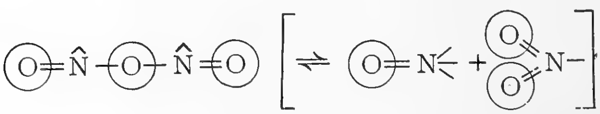
There are also residual electrostatic forces to be considered. It has long been recognized that the bond in a molecule like HCl is electrostatic, and owes its existence to the extraction of an electron from the H atom by the Cl atom, whatever may be the cause of that extraction. The electrical polarity which presumably is thus set up in the molecule has been used to explain many phenomena by Sir J. J. Thomson in a recent paper on "The Forces between Atoms and Chemical Affinity" (Phil. Mag., May, 1914); also a discussion of this effect from a more chemical standpoint is given by G. N. Lewis in a paper on "Valence and Tautomerism" (Journ. Amer. Chem. Soc., 1448-1455, 1913), and by others. Now the explanations of the magnitude of the dielectric constant, extent of molecular association, and other things, by means of this conception are not affected by the assumptions of the present theory (except in so far as they may in some cases be made more definite); but a part of the phenomena

which it has been attempted to explain as due to electrostatic induction between molecules will be found to be more plausibly ascribed to a magnetic induction. It should be noted that the electrostatic induction, which must of course occur, would often have much the same effect as the magnetic induction described above, especially in actions between separate molecules; but there is much in the *intra*-molecular influences in carbon compounds that can be explained by the latter conception only. This I hope to discuss in a future paper, but it may be pointed out now that the two effects (electrostatic and magnetic) are closely interdependent, according to the present theory, for electric polarization of a molecule has its origin in a rearrangement of magnetons to form the group of eight.

§12. Unsaturation in Inorganic Compounds

This only occurs when an atom, acting positively, has a valence less than its maximum; for negative valence is fixed—for example, an atom with six valence magnetons can part with any number up to six, but to make up a group of eight within itself it must take in exactly two. The formulæ

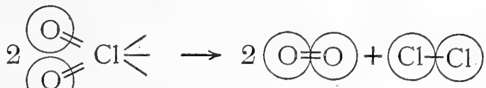




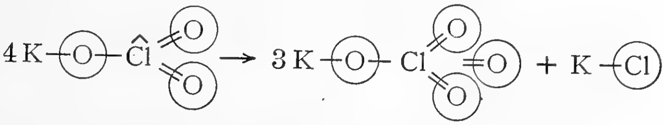
explain themselves. In most of such molecules the unsaturated atom has a pair of free magnetons, which is represented by the symbol $\wedge$. This tendency of free magnetons to go in pairs is referred to again below.

Now these free magnetons may be expected to produce two effects in the molecule. One is obvious: it is a tendency to form the corresponding saturated molecule, CO_2, PCl_5, SO_3, N_2O_5, N_2O_4, and so lower the magnetic energy. But this must always raise the electric energy—*e. g.*, in SO_2 the S atom has lost four magnetons, in SO_3 six—and that tends to oppose saturation. The point of equilibrium between these two tendencies, apart from metastable conditions of the molecule, will naturally be further and further from the point of saturation as we pass from group IV to group VIII of the Periodic Scheme: an inspection of the oxides in these groups shows that this prediction agrees with the facts.

The other effect is due to their influence upon what linkages are already formed. We have seen (§11) that free magnetons weaken neighboring groups of eight. This results in a tendency for unsaturated molecules to break down in such a way as to form molecules of other types that are more saturated, if that is possible. This may occasionally take place by the formation of the molecules of the elements, as in the reaction

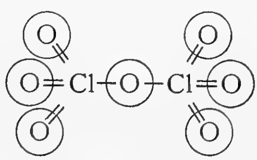
 . . . . .A,

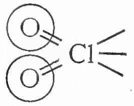
but more often by a change of the following type:

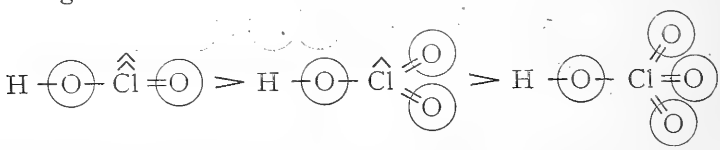
 . . .B,

which combines the two effects of the free magnetons.

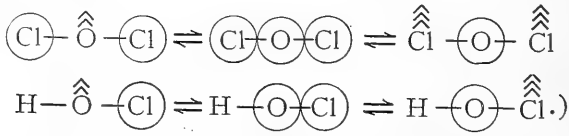
Changes of type A do not take place readily unless the resulting elementary molecules are well saturated in character, for if they are not, the reverse action readily occurs. The nature of elementary molecules cannot be discussed at this stage; but it is noteworthy that the high molecular weights of gaseous Sulphur and Phosphorus and the high melting points of Carbon and Silicon are in accordance with the fact that their oxides, even when unsaturated, do not break down into the constituent elements; while the metastable nature of the oxides of Nitrogen is in accordance with the saturated character of the N_2 molecule. The facts in these cases could have been predicted, quite independently of any theory, from the mere conception of unsaturation; but the same cannot be said of the comparisons which now follow.

To see clearly the effect of free magnetons in loosening linkages, it is necessary to compare the Oxygen compounds of some element whose oxides are all metastable, that is, an element which will not combine directly with Oxygen at all. Thus we eliminate the reverse action which confuses the issue in the case of Sulphur, Carbon, etc. Fluorine and Oxygen are too extremely negative to possess oxides (except for O_3), but we have an ideal case in Chlorine. Of the oxides of Chlorine,  is found to decompose

less readily than  ; and this remarkable result is only to be explained by the absence of free magnetons from the molecule of the former, for that oxide must have much the higher electric energy of the two. In the case of the oxyacids of Chlorine, the velocities of decomposition, under equal conditions, are in the following order:



and the same is true for their Potassium salts. Also the heat evolution for complete conversion into KCl+Oxygen is much greater for $KClO_3$ than for $KClO_4$, and very probably is greater still for $KClO_2$. (I have left Cl_2O and HOCl out of account, because they contain the negative bond, thus:

and 

For Bromine and Iodine the relations are less regular: $HBrO_4$ is not known, and $HIO_4(2H_2O)$ is less stable than HIO_3. In the case of Nitrogen the oxyacids obey the rule, but most of the oxides do not. No other negative elements satisfy the condition of not combining directly with Oxygen.

As examples of changes of the type B, we have the following that take place on heating:

$$\left.\begin{array}{l} 4\mathit{KClO_3} \rightarrow 3KClO_4 + KCl \\ 3\mathit{HClO_3} \rightarrow HClO_4 + H_2O + 2\mathit{ClO_2} \end{array}\right\} \text{group VII,}$$

$$4\mathit{Na_2SO_3} \rightarrow 3Na_2SO_4 + Na_2S \quad \} \text{group VI,}$$

$$\left.\begin{array}{l} 4\mathit{H_3PO_3}\text{ aq.} \rightarrow 3H_3PO_4 + PH_3 \\ 5\mathit{Na_3AsO_3} \rightarrow 3Na_3AsO_4 + 3Na_2O + \mathit{As} \end{array}\right\} \text{group V;}$$

and others that are spontaneous at ordinary temperatures:

$$3\mathit{H_2MnO_4}\text{ aq.} \rightarrow 2H_2MnO_4 + 2H_2O + \mathit{MnO_2} \quad \} \text{group VII,}$$

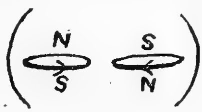
$$3\mathit{HNO_2}\text{ aq.} \rightarrow HNO_3 + H_2O + 2\mathit{NO} \quad \} \text{group V,}$$

$$2\mathit{Na_2SnO_2}\text{ aq.} \rightarrow Na_2SnO_3 + 2NaOH + \mathit{Sn} \quad \} \text{group IV.}$$

(Unsaturated molecules are italicized throughout.) The effect thus seems very general, although it will be recognized that two or three

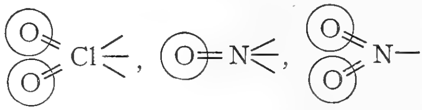
of these examples may not have much significance. In many cases (as with nitrites, bromates, iodates) such changes have not been observed, but when it is remembered that the electric strain is invariably greater in the saturated than in the unsaturated molecule, it seems that the evidence here collected is enough to establish the principle of the interfering action of free magnetons.

A difficulty in interpreting the chemical data arises from the fact that, although a reaction will not take place at all unless it causes a diminution in free energy, the velocity of the reaction is very little dependent upon the amount of that diminution. It seems, on consideration, that the loosening effect of the presence of free magnetons ought to have a more definite effect in accelerating a change (as in the decomposition of the oxyacids of Chlorine) than in conditioning it, thus resembling a catalyst: for it is impossible to predict whether the magnetic energy due to the presence of free magnetons in the molecule would or would not be greater than the increase in electric energy which accompanies saturation. In the case of a reaction like $4K\hat{Cl}O_3 \rightarrow 3KClO_4 + KCl$, however, it should be noticed that while the magnetic energy of all four molecules is diminished, the electric energy increases in only three of them, being greatly diminished in the fourth.

The rule (with numerous exceptions) that the positive valence of an atom, when it has not its maximum value, has a value that is less than that by two units, is in accordance with the present conceptions; because a group of two magnetons 

not only has considerably less than twice the magnetic energy of a single magneton, but on account of its nature will interfere less with the stability of a group of eight, for the latter is made up of four such pairs. A group of three, whatever its configuration, must have as great a disturbing effect as a single magneton. Again, four free magnetons probably could not maintain a compact symmetrical configuration, because they lie in an outer layer of the atom (§§7, 14), and would probably be distributed so as to act like two groups of two, thus causing about twice the amount of disturbance that one of these can cause: in accordance with this, we find that molecules like $Cl - \hat{\hat{S}} - Cl$ and $H - O - \hat{\hat{Cl}} = O$ are quite rare, and very unstable.

The exceptional cases



can reasonably be attributed to the fact that in the case of penta- and hepta-valent elements those oxides which have an *even* number of free magnetons in the atom are bound to have cumbrous molecules like $\text{O} = \hat{\text{N}} - \text{O} - \hat{\text{N}} = \text{O}$.[1]

The frequent occurrence of a pair of magnetons as a subsidiary group in the outer part of the atom, and its comparative stability, are the reasons for the use here of the symbol $\wedge$ to represent it.

Unsaturation in Carbon compounds is quite a different kind of phenomenon and will not be discussed in the present paper.

§13. The Transition Series of Elements

In §6 constitutions were assigned to the elements of the series as follows:

Ti	V	Cr	Mn	(Fe Co Ni)	Cu	Zn	Ga	Ge
$(3\gamma+)$ 4	$\bar{5}$	$\bar{6}$	$\bar{7}$	$\bar{8}$	$\bar{9}$	$\overline{10}$	$[\overline{11}]$	
$(4\gamma+)$					[1]	2	3	4

They were based on an arbitrary assumption—that in certain specified cases (*i. e.*, in the middle of the long periods) the group of eight was not formed by eight or more free magnetons. The justification for this is that it enables us, without any further assumptions whatever, to systematize and explain the outstanding properties—at first sight so irregular—of these elements.

In the first place, some of the properties of the first four are quite normal. For example, Mn, which is $3\gamma+7$, although without negative action, has a positive valence of seven, as is shown in Mn_2O_7 (*cf.* Cl_2O_7) and $KMnO_4$ (which is isomorphous with $KClO_4$). Similarly, in the nature of their higher oxygen derivatives, V and Cr

[1] The kinetic effect here implied should of course be taken into account continually in any complete analysis of the behavior of atoms, but it is difficult to see how this can be done even in a qualitative way except in the very simplest cases.

resemble P and S. The elements Fe, Co, Ni have been given the constitution $3\gamma+\bar{8}$, and, although they themselves are not known to be octovalent, the analogous elements Ru $(5\gamma+\bar{8})$ and Os $(9\gamma+\bar{8})$ give the oxides RuO_4 and OsO_4.

Again, Cu, Zn, and Ga, the last three of the series, give compounds in which they are mono-, di-, and tri-valent respectively, thus resembling the typical elements of the groups I, II, and III, in which they lie. Now we have seen (§7) that the atoms of these elements may be supposed to undergo an intra-atomic tautomerism similar to the intra-molecular tautomerism described for CH_4, NH_3, OH_2, HF, in §9; and, as in that case, brackets have been used to represent roughly the proportions we may expect of the two phases. What we should predict from this is true in fact, for the first long period at all events: compounds of monovalent Cu (from the $4\gamma+1$ phase) are less stable than those of divalent Cu (from the $3\gamma+\bar{9}$ phase, as explained below), while compounds of trivalent Ga (from the $4\gamma+3$ phase) are stabler than the other compounds of Ga. In the case of Zn, it will be shown that both phases make for divalency. For the other two long periods the agreement is not so good.

In addition to the individual properties already referred to, all the elements of this series give basic oxides in which the atom of the metal tends to be trivalent towards the left of the series, and divalent towards the right. The very regularity of this series of oxides indicates that they are in some way due to the 3γ phases of these atoms: $(3\gamma+)$ $5, \bar{6}, 7, \bar{8}, 9, \overline{10}, \overline{11}$; but the connection seems at first sight to be remote. It appears as if the successive additions of magnetons have a very slight effect in these transitional series, as far as the basic oxides are concerned (compare with this the even greater monotony in the series of rare-earth elements: see the table of the Periodic Scheme at the end of §7).

Of course Cu, for example, could not be expected to give stable salts in which it is 9-valent, such as $CuCl_9$, not only because of the mechanical hindrance to this, but also because the extraction of so many magnetons from the Cu atom would have to be effected against comparatively great electrostatic forces: towards *negative* groups the atom must remain unsaturated, and some of its nine magnetons will be free. This brings us to yet another application of the principle of the disturbing action of free magnetons, which was discussed in §12. We get the result, paradoxical at first sight, that the more free magnetons an atom possesses, the fewer it can use to combine with negative radicles—unless it succeeds in using them all, which is not

possible beyond a certain number (*cf.* the instability of Cl_2O_7 and Mn_2O_7). This would account for the steady progress from trivalence to divalence that has just been noted. Subjoined is a list of the valences of the transition metals in their chlorides:

	X_2O_5	XO_3	X_2O_7	XO_4	← Saturated oxides		
	V	Cr	Mn	(Fe Co Ni)	Cu	Zn	Ga
	4	..	4	.. .. ..	..	..	..
3γ	**3**	**3**	3	**3** 3 3	..	..	**(3)**
	2	2	**2**	2 **2** **2**	**2**	**(2)**	2
	..	..	..	.. .. ..	(1)	..	1
	Nb	Mo	—	(Ru Rh Pd)	Ag	Cd	In
	5	5	..	.. .. ..	..	..	..
	..	4	..	**4** 4 4	..	..	..
5γ	**3**	**3**	..	**3** **3** ..	..	..	**(3)**
	2?	2	..	2 2 **2**	..	**(2)**	2
	..	..	..	.. .. ..	**(1)**	..	1
	Ta	W	—	(Os Ir Pt)	Au	Hg	Tl
	5	5	..	.. .. ..	..	..	..
	4	**4**	..	**4** **4** **4**	..	..	..
9γ	3	..	..	3 **3** ..	**3**	..	(3)
	..	2	..	2 2 2	2?	**(2)**	..
	..	..	..	.. .. ..	(1)	1?	**1**
+	$\bar{5}$	$\bar{6}$	$\bar{7}$	$\bar{8}$	$\bar{9}$ $\downarrow\uparrow$ $[\gamma+1]$	$\overline{10}$ $\downarrow\uparrow$ $\gamma+2$	$[\overline{11}]$ $\downarrow\uparrow$ $\gamma+3$

The numbers in heavy type represent the chlorides that are stablest to oxidation or reduction (as far as the relations could be ascertained), and the decrease in effective valence from left to right is brought out clearly. The values in parentheses do not of necessity belong to this scheme, but can be due to the other phase of the atom's structure: however, the tendencies of the two phases may coincide, as in the case of Zn, Cd, and Hg. (Monovalent Hg, in the

sense in which Ag is monovalent, is of doubtful existence, for the mercurous ion has been shown to be double: Hg_2^{++}.)

The case of Ag is remarkable. We would certainly expect $AgCl_2$ or $AgCl_3$ to exist, even if they were not as stable as AgCl, but Ag is monovalent in its salts almost without exception. However, this atom's power to form complex ions, which, as I hope to show later, is a characteristic property of these unsaturated atoms and conditioned by their unsaturation, is good evidence for the existence of the $3\gamma+\bar{9}$ phase.

The whole of this explanation, apart from its simplicity and consistency, is strongly supported by the nature of the physical properties of these elements; for there is marked parallelism between their high melting points, electrical conductivities, and magnetic susceptibilities, and the large numbers of free magnetons in their atoms. Their small atomic volumes are also in accordance with the results of this paper, as may be seen in the next section (§14).

PART IV. VOLUME

§14. The Volume of the Positive Sphere

The atomic volume of an element in the liquid or solid state is, as is well known, far from being, even approximately, a simple function of its atomic weight, or of the number of magnetons that are in the atom according to the present theory. The elements at the maxima of the well-known atomic volumes curve have atomic volumes that are about seven times as great as those of the elements at the minima. The periodic nature of these fluctuations, however, and their obvious relation to fluctuations in other properties of the elements, such as their valences or melting points (the relation being of an inverse character in these two cases), have made it fairly clear that they are to be ascribed to differences in the forces acting between atoms rather than to corresponding fluctuations in the volumes that the atoms might have if they could be isolated.

This is the "Hypothesis of Compressible Atoms" for which T. W. Richards has brought forward many kinds of evidence (Faraday Lecture, 1911; Journ. Amer. Chem. Soc., 36, 617-634, 1914; etc.); and the final justification for bringing this idea very concretely into the present theory (which has already been done in §7) is that the elements which lie along the minima of the atomic volumes curve are just those to which we have ascribed the maximum numbers of magnetons not bound in groups of eight or tending to form them (the constitutions assigned to (Fe Co Ni), Cu, Zn, Ga, and their ana-

logues being, in that respect, the new features of the present treatment, §§7, 13). Also the fact that the maxima of magnetic susceptibility are almost coincident with the minima of atomic volumes (even in the case of Cu salts) takes on a new significance when the forces between atoms are attributed to specific attractions between magnetons, as they are here.

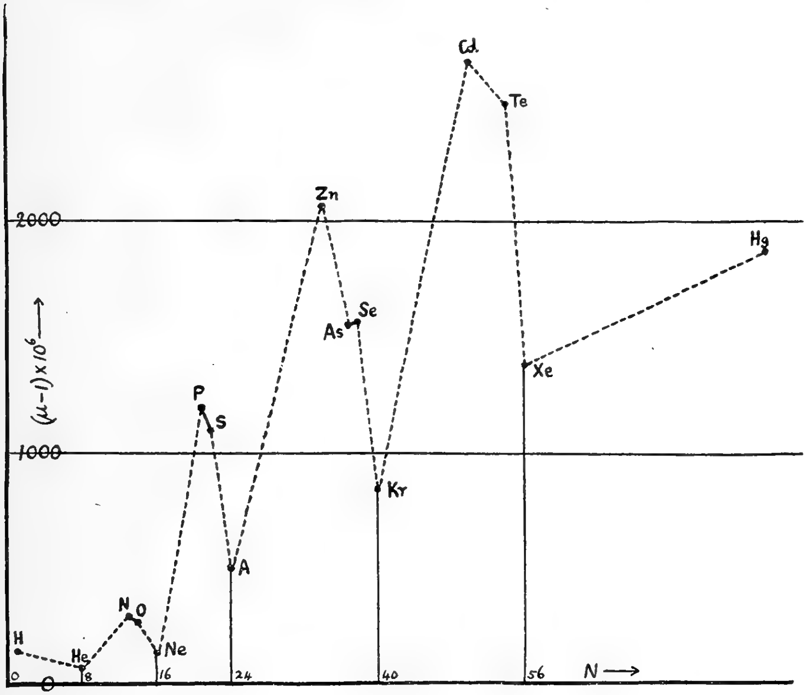
Evidence about the volumes of isolated atoms is not entirely lacking; and, as might be expected, it has been got from the behavior of gases, especially those with monatomic molecules. If μ is the refractive index of a monatomic gas for very long waves, and the atom is assumed to be made up of electrons within a uniform positive sphere, it can be shown that $\mu - 1$ is proportional to the volume of this sphere. Values for μ have been got for various gaseous elements by Cuthbertson and Metcalfe (Phil. Trans. A., 207, 138, 1907), and the corresponding values for μ-1 are tabulated in Thomson's "Corpuscular Theory of Matter," chap. VII, p. 165. I have tabulated them below together with the atomic volumes of the elements in the solid or liquid state, their atomic weights, and their magneton numbers (N).

	Atomic weight	Atomic volume		$(\mu-1)\times 10^6$ ∝ gaseous atomic volume	N ∝ Normal volume of the positive sphere
		Solid	Liquid		
*Hydrogen ..	1	13.1	14.3	139	1
Helium......	4	....	27.4	72	8
Neon........	20	....	——	137	16
Argon.......	40	....	28.1	507	24
Krypton......	82	....	37.9	850	40
Xenon.......	128	....	36.4	1378	56
Zinc.........	65	9.2	....	2060	34
Cadmium.....	112	13.0	....	2675	50
Mercury.....	200	....	14.7	1866	82
*Oxygen.....	16	11.2	12.6	270	14
*Sulphur	32	15.5	....	1101	22
*Selenium....	79	16.5	....	1565	38
*Tellurium ..	128	20.4	....	2495	54
*Nitrogen ...	14	13.6	16.9	297	13
*Phosphorus.	31	14.1	....	1197	21
*Arsenic.....	75	16.0	....	1550	37

* Not monatomic.

It may be seen from this table that the values of $\mu - 1$ for the elements of any group show a much greater parallelism to the magneton numbers than do the ordinary atomic volumes (except in the single case of Hg); but if these values are plotted against the

magneton numbers to give a curve of gaseous atomic volumes as shown below, a much more striking relation is brought out. In-

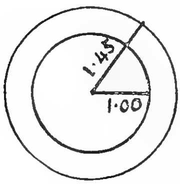


complete as this curve is, it may be seen that its maxima correspond closely to the minima of the ordinary atomic volumes curve. It is true that the $\mu - 1$ relation holds in strictness for monatomic gases only, but if O, N, P, S, etc., could be obtained in the monatomic state, their values for $\mu - 1$ would almost certainly be even higher than they are here, for the atoms in a polyatomic molecule must be somewhat compressed.

It seems then that the presence of a large number of valence magnetons, which we have held responsible for the abnormally low atomic volumes of some solid elements, is accompanied by an abnormally high atomic volume in the case of gaseous elements. This result, remarkable as it may seem at first, is not at all out of harmony with the present assumptions: indeed, the curve of gaseous atomic volumes is easier to explain than the other.

We saw in §7 that the extent of the compression of the positive sphere depended in part upon the magnetic attractions between the magnetons. Now when an atom contains valence magnetons (*i. e.,*

magnetons not in groups of eight), the average magnetic energy per magneton is higher and the average attractions between the magnetons are less. Since the valence magnetons are distinct from the others (as an average effect at all events), this will show itself chiefly in the existence of a rather less compressed outer layer in which the valence magnetons lie, but partly also in an expansion of the groups of eight in the atom owing to the disturbing effect described in §11.



The total result is thus an expansion of the atom, the amount of which must be roughly proportional to the number of valence magnetons in it. Hence we would expect a periodic fluctuation of the atom's normal volume just like that in the curve given above. There, the maximum volumes are about three times as great as the minimum, but it should be borne in mind that this only means a 45 per cent increase in the radius of the atom for the transfer of about one-third of its magnetons from a closely to a loosely bound condition.

The abnormally high value of $\mu - 1$ for Hydrogen is not entirely unexpected, because, although the positive spheres of all atoms are internally compressed to the same extent by electrostatic forces (§7), the Hydrogen atom is the only one that is not further compressed by internal magnetic forces, for it contains only one magneton. Even in the H_2 molecule the compression cannot be nearly so great as in the Helium atom; so that the volume of the positive sphere of the atom of gaseous Hydrogen may be expected to be abnormally great—if not quite so great as the $\mu - 1$ relation indicates.

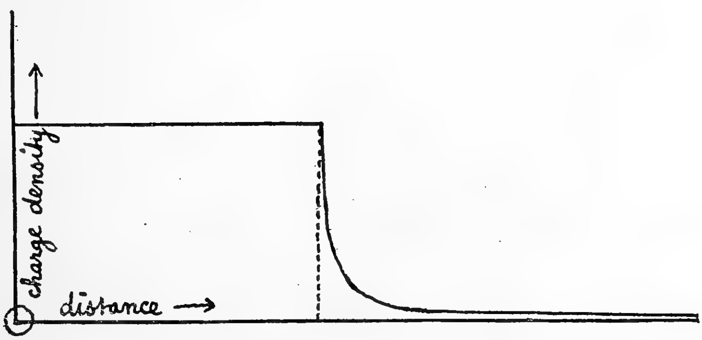
§15. Atomic Volumes in the Liquid and Solid States

In considering now the volumes of atoms in liquids and solids, it might loosely be taken for granted that the action of valence magnetons on atoms such as I have hitherto described could produce the differences in volume that are observed. This involves a fallacy, the avoidance of which leads to an important conclusion about the distribution of the atom's positive sphere, which up to the present has been assumed to be uniform in the absence of magnetons.

If a naturally uniform positive sphere contains magnetons proportional in number to its charge (and normal volume), which are not attached to it except by electrostatic forces, the average compression in a cluster of such spheres must be about the same whether the magnetic forces are acting almost entirely within the separate

spheres, or are acting largely between them, and so the average volume per magneton should be about the same in the two cases. If there is any difference at all between the two cases, it is that the cluster in which the forces between atoms are considerable will be compressed even less than the other; because it is rarely possible for valence magnetons to reach a state of such low magnetic energy as exists in an atom where the magnetic forces are acting almost entirely within the atom owing to all its magnetons being in groups of eight. Even in the case of a molecule like H-Cl, where it is true that all the magnetons are in groups of eight, the electrostatic strain must increase their magnetic energy and expand the groups somewhat.

This theoretical result is of course directly at variance with the facts. A cluster of atoms of Argon (3γ) or of Krypton (5γ) has about four times the volume per magneton of a cluster of Iron, Cobalt, or Nickel atoms ($3\gamma+\overline{8}$); and a similar relation holds between Helium atoms (γ) and Carbon atoms ($\gamma+4$). The great decrease in volume that is undoubtedly caused by an increase of the magnetic forces between the atoms at the expense of the magnetic forces within the atoms is much more than a filling in of "spaces" could account for, and can have only one explanation: the positive sphere must have a much lower charge density and a much greater compressibility at its boundary than in its interior; and thus the compression of this boundary layer, since it is due to the action of the valence magnetons chiefly, is found to be a "periodic" effect as the atomic weight increases.



This boundary layer, which I shall call the *envelope* of the atom, will be assumed to exist quite independently of the action of magnetons upon the positive sphere, and may reasonably be supposed to

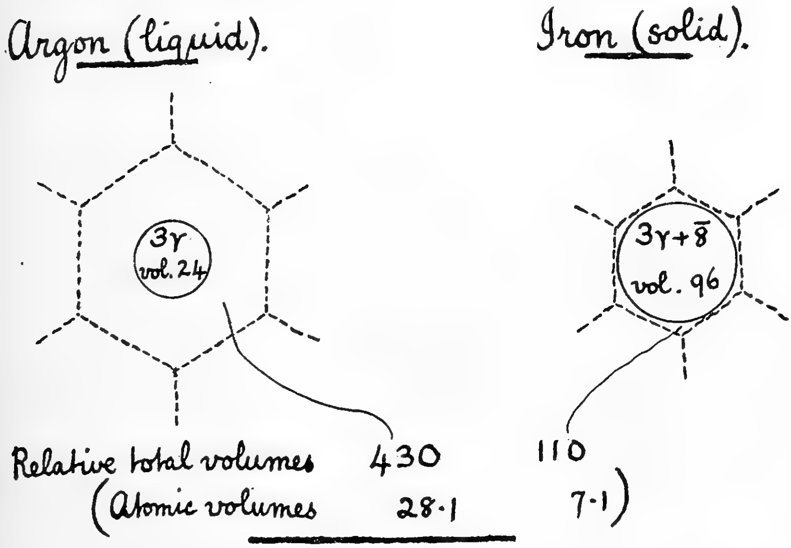
be of the same thickness for all atoms, since it abuts upon a positive sphere which has the same normal charge density for them all. It may be of uniform density, but it seems more natural to suppose that its density falls off rapidly as the distance from its inner boundary increases,[1] as shown in the diagram, where O represents the center of the atom. With regard to its extent in the case of an isolated atom there is no need to speculate. If it is to fulfill the purpose for which its existence was assumed, it must be supposed to have so low a charge density that magnetons do not lie in it, and therefore its presence does not appreciably affect the values of $\mu-1$ (§14). As being by far the most compressible part of the atom, the envelope is the seat of the greater part of the volume change that accompanies a chemical or physical change, and it may be supposed to be compressed into a very small space when the forces between atoms are strong.

This envelope, the assumption of which will enable us to give a qualitative explanation of practically all the observed volume relations, must be distinguished from the comparatively very dense layer in which the valence magnetons lie as they surround the groups of eight, and which owes its existence entirely to the presence of the valence magnetons, being simply a less compressed part of the positive sphere proper (see §14). In the diagrams hitherto used in this paper, both this layer and the envelope have been disregarded, but they are represented in the more complete diagrams which are given below for the atoms of Argon (3γ) and Iron ($3\gamma+\bar{8}$) when these elements are in the liquid and solid states respectively. Their magneton numbers are 24 and 32, but because of the expanding effect of the valence magnetons (which approximately trebles the volume: see §14), the volumes of their positive spheres, neglecting the envelopes, are 24 and 96 respectively (in arbitrary units). These are represented by the circles in the diagrams. The dotted hexagon represents the total space, frequently duodecahedral in shape, that is occupied by the atom when it is one of a cluster. In the case of Iron, this space is shown as being only a little greater than the volume of the positive sphere proper; *i. e.*, about 110 units. The total space for the Argon atom is therefore represented as having a volume of about 430 units, to accord with the relative atomic volumes observed for these elements. It may be seen that the distances across which the interatomic forces must act are thus made to be about as we

[1] This gives the "thickness" a meaning even if the envelope is infinite in extent.

would expect from what is known of the cohesion of these two substances, especially in view of the fact that the Iron atom has eight valence magnetons and the Argon atom none. The assumption that the envelope of the Iron atom is already compressed to a very small volume (as shown in the figure) is justified by the exceedingly low compressibility of this element—as found by T. W. Richards.

The curve of atomic volumes.—Owing to the complexity of the factors involved, it is useless to try to make up an expression that would yield a complete atomic volumes curve; but it is nevertheless possible to predict a number of the features of such a curve.



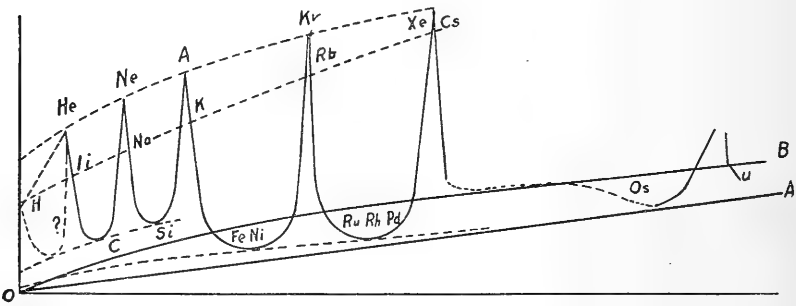
In the first place, the force that compresses the atoms is likely to come chiefly from the valence magnetons, and to a less extent from the groups of eight in the atom. Now the slight cohesion of the inert elements shows that the latter factor is small enough to be neglected when there are valence magnetons present—in the present rough treatment at any rate. It is important, however, to find out the effective numbers of the valence magnetons in the various atoms. That these are not necessarily the same as the actual numbers may readily be seen by comparing the probable behavior of Cl $(2\gamma+7)$ with that of Mn $(3\gamma+\bar{7})$. The former has a strong tendency to form the group of eight, and so in its cohesive action it will behave as if it contained fewer than seven magnetons. This argument applies to all the halogens, and to a less extent to the nega-

tive elements of groups VI and V of the Periodic Scheme. Thus in the short periods the effective numbers of magnetons will be nearer to *1 2 3 4 3 2 1*
than to 1 2 3 4 5 6 7, although this almost certainly underestimates the numbers in groups V-VII. Similarly, in the long periods we can substitute for the actual numbers, which are

1 2 3 4 5 6 7 8 9 10 (11)
(1) 2 3 4 5 6 7, the effective

numbers: *1 2 3 4 5 6 7 8 7 6 5 4 3 2 1.* The use of these numbers (in italics) would place C and Si at the minima of the curve in the short periods, and Fe Co Ni and the Platinum metals at the minima in the long periods—as they are in the curve of actual atomic volumes.

With regard to the shape of the curve, since the envelope, as we have pictured it, is bound to be more compressible at small than at great compressions, we could predict the flat minima and peaked maxima that are observed, and would expect, from what has been said, a curve of the general shape shown in the figure (the signifi-



cance of the " dotted " loci is explained below). The chief defect in this curve is that it places all the inert elements at the maxima. In actual fact He is at the first maximum, and Ne probably at the second (its density in the liquid state has apparently not been determined), but the other maxima are occupied by the alkali metals K, Rb, Cs. Now although it is difficult to explain why the atomic volumes of these elements should be greater than those of A, Kr, Xe, it is easy to see why they should not be very much less. When each atom in a cluster has only one valence magneton, the chance that the valence magnetons will cooperate effectively to compress the cluster is very small, and much less, for example, than one-fourth of the chance when each atom contains four—not only because of their small

number, but also because the greater depth of the atom's envelope (due to the smaller compression) makes it less likely that the magnetons will be able to maintain the most favorable attitudes. Most of their action will be upon groups of eight, for which their attraction is slight. Also this difficulty will increase as N (and the size of the atom) increases: this is represented by the locus for the alkali metals in the above diagram. For similar reasons the elements Be, Mg, Ca, Sr, Ba would lie rather higher on the curve than might at first have been expected.

Now if the atoms had no envelopes, and all their magnetons were in groups of eight, their volumes would be nearly (but not quite: see *a*, below) proportional to their magneton numbers, and they would lie on a straight line such as OA in the diagram. But for any series of analogous elements the volume will not increase as fast as N, for three reasons:

a. Even the volume of the positive sphere proper does not increase quite as fast as N, because the amount of compression due to internal magnetic forces increases somewhat as N increases: this makes most difference in the case of H (see §14).

b. The expanding effect of a given number of valence magnetons (§14) becomes proportionately less as N increases. The locus of the atomic volumes of the elements with $\bar{8}$ valence magnetons will then be about as I have drawn it through the minima of the curve, it being assumed for simplicity (and the flatness of the minima fairly justifies the assumption) that the envelope has practically disappeared in these cases. There will probably be some envelope left in C and Si: hence their positions.

c. The addition of the envelope will increase the volume of a small positive sphere proportionately more than that of a large one, for the envelope has been assumed to be of the same "thickness" for all atoms; thus, if two spheres with radii in the ratio 1:2 (volumes 1:8) have added to each of them an envelope with a thickness equal to the radius of the larger, their new radii are in the ratio 3:4, and their volumes now 27:64—a very different ratio. This effect, while it is more important for H than for any other single atom, will affect the series of inert elements more than any other series, for their envelopes should be less compressed than those of other elements: this is shown by the locus in the diagram. The actual relation in the case of these elements is in excess of the prediction, for the atomic volumes scarcely increase at all as N increases, that of Argon being even less than that of Helium: but valence magnetons are absent,

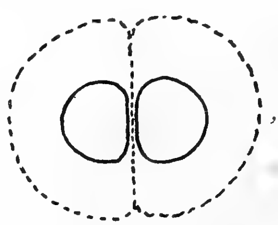
and the compression is due entirely to the action of the increasing number of groups of eight—which might account for the increasing compression, though, on consideration, it cannot be definitely said that it would.

There is another reason why atomic volumes should not increase as fast as *N*, which is not general but applies only to the halogens and the other "negative" elements for which we chose corrected "effective numbers" on account of their tendency to form the group of eight. This tendency to form the group of eight will be diminished as *N* increases;[1] hence the effective number of valence magnetons will be increased.

In this unavoidably involved set of predictions there is still another factor to be taken into account. As the surface of the atom increases with *N*, the average force on unit area that is caused by the action of a given number of valence magnetons must diminish—more rapidly at first than for large values of *N*. This will be true for all except the inert elements (see *c*, above). Hence, as *N* increases, atomic volumes (except for He, Ne, etc.) will increase faster than we have supposed, and the final predicted curve could be got from the curve in the diagram by multiplying the separate values which it represents by a set of factors whose relative magnitudes are roughly indicated by the curved line *OB*.

The extremely qualitative and even uncertain nature of this reasoning is very apparent, but it is the best that can be done under the circumstances.

If atoms have envelopes, as has been assumed in this section, we would expect the envelopes in a diatomic gas molecule to be distributed somewhat as follows:



the compressions due to collisions (see T. W. Richards, Journ. Amer. Chem. Soc., 36, 617-634, 1914) affecting the envelopes chiefly. The advantage of this idea is obvious, for if polyatomic molecules were

[1] This effect has not been alluded to as yet, but it is doubtless connected with the fact that as the number of groups of eight in the atom increases, the valence magnetons must be more and more scattered.

not "padded" into a more or less approximately spherical shape in some such way as this, they would be expected to dissociate more readily than they do in actual fact. This padding need not be so complete as to abolish the so-called energy of rotation.

With regard to the assumptions that have been made in this paper about the existence, distribution, and compressibility of the positive sphere, it might be argued that a reference of the ordinary superficial conceptions of volume and compressibility to a more fundamental conception that is equally gross is no explanation at all. But a simplification has undoubtedly been made by the present method.

Again, it is obviously desirable to avoid a multiplicity of fundamental concepts; but it has not hitherto been found possible to base any theory of the constitution of matter upon a single concept. For example, the nearest approach that has as yet been made to such a fundamental concept is the electric charge. Now, in the first place, this cannot explain observed mass relations except through the idea of the volume of a charge. In the second place, an electric charge, if it is nothing more than that, must be dissipated throughout all space on account of the repulsions between the separate portions of it. Thus the various ideas of the electron, the magneton here described, the uniform sphere of positive electrification of Kelvin and Thomson, and the minute positive nucleus of Rutherford, all imply the existence of some *non-electric constraint* which has essentially the same kind of action upon the electric charge as the forces of cohesion have upon gross matter. If then the introduction of this idea is necessary, as it seems to be, it is both legitimate and useful to develop it to its fullest possible extent.

§16. Summary of Assumptions, etc.

I have attempted in the foregoing pages to show that this magneton theory can go a long way towards explaining the most diverse kinds of chemical combination; and further applications, to phenomena such as those of ionization (§9), the formation of complex salts and molecular compounds (§13), and the structural influences in the molecules of Carbon compounds (§11), have been suggested. Before these latter can be adequately dealt with, however, one other factor in the behavior of magnetons must be studied: this is the electrostatic retaining force which opposes the extraction of a magneton from its parent atom (see Kelvin's analogy, §4), and is important because it determines the strength of a linkage and sometimes its mode of dissociation also.

Quite another field opens up before this theory in the physical properties of matter, for it has professed to take into account, in a qualitative way, most or all of the factors in the action of atoms upon one another. The interaction of magnetons and "positive spheres" should account not only for the chemical properties of the elements and their compounds, but also for their melting and boiling points, tenacities, atomic volumes under various conditions (already touched upon in §§14, 15), electrical conductivities, and, above all, for their magnetic properties (see §§2, 13 and Part V). It is evident, however, that the application of the theory to the details of these phenomena must be a very complex and difficult matter.

I will conclude this part of the work by summarizing the assumptions made in the course of it, and the working material derived from them.

ASSUMPTIONS

1. The atom is made up of a positive part and *magnetons,* which are ring-shaped negative charges (hitherto called electrons and supposed to be spherical or concentrated at a point) rotating with a peripheral velocity of the order of that of light, their radii being comparable with but less than that of the atom (§1). Their rotation is independent of any attracting positive charge.

2. The positive part of the atom is a sphere of uniform positive electrification, with the properties of an elastic solid (§§7, 14), and with a volume *normally* proportional to the number of magnetons it contains (§1). It is surrounded by an atmosphere or envelope of very low charge density, which is also elastic (§15).

3. The formation of the group of eight (of low magnetic energy), which is practically proved for a system of eight magnetons, is assumed to take place also in atoms containing more than eight. [This is not altogether an assumption, as the reasoning in §7 shows.]

4. To explain the occurrence of long periods in the Periodic Scheme, and at the same time the properties of the elements in these periods (§§13, 15), it is necessary to assume that there is in certain cases a hindrance to the formation of a group of eight when it is normally due. [An arbitrary assumption: see §7.]

The last two, although they come early in the development of the theory, are assumptions which it would be very desirable to avoid: further study of the behavior of magnetons or some alteration in the more fundamental assumptions may make this possible.

These assumptions have furnished the following factors in the behavior of magnetons, atoms, and molecules:

1. The simple magnetic attraction between two magnetons (§5).

2. The tendency to form the group of eight (§6).

3. The residual magnetic forces exerted by all combinations of magnetons: their attracting and inducing actions (§11).

4. The electric polarization set up by the extraction of a magneton from one atom by another atom: its attracting and inducing actions (§11).

5. The effect upon the nature of a linkage of the electrostatic retaining power of an atom for magnetons (not yet discussed).

6. The pressure and volume changes that are possible in the positive sphere, and more particularly in the envelope, of the atom (§§14, 15).

In quantity and variety this working material far surpasses that which is afforded by any purely electrostatic theory of the atom (and strictly speaking, no theory is purely electrostatic: see §15).

This work was done largely in England, but has been amplified and completed at Harvard University and at the University of California.

NOTE.—Besides his work on radiation, which is not confined to the paper mentioned in §1, Dr. Webster has made an important addition to this theory in suggesting that a minute nucleus could be added to the model atom here described, without much affecting the behavior of its other parts if the nucleus were neutral or nearly so. This, which I have only mentioned casually in §8, will be discussed in connection with α-particle scattering and other matters in a forthcoming paper by him.

PART V. MAGNETISM

§17. The Radius and Moment of the Magneton

From the results of the last section it is possible to calculate approximately the radius of the magneton, starting from the assumption originally made that it is about half that of the positive sphere of the Hydrogen atom. Since that assumption was made, however, we have seen that the radius of the Hydrogen atom's positive sphere is a less significant quantity than that of the positive sphere of a large atom, because Hydrogen is exceptional in having no internal magnetic compression and therefore has an abnormally large positive sphere.

Since the volume (V) of the positive sphere of a large atom is nearly proportional to its magneton number (N), the radius of the magneton which has been used to construct atoms in the preceding section will be about $\frac{1}{2} \times \sqrt[3]{\frac{V}{\frac{4}{3}\pi N}}$. Now values for V, though not experimentally accessible for most atoms, are given by the ordinary

atomic volumes in the case of those elements in which the compression is reasonably supposed to be so great that the envelope has practically vanished (see §15). Such are Iron and Platinum. Dividing the atomic volumes of these by Avogadro's constant (6.0×10^{23}), we get 11.4×10^{-24} and 14.6×10^{-24} as values for V in the two cases. Since their respective magneton numbers are 32 and 80, the two values 2.2×10^{-9} and 1.8×10^{-9} are got for the magneton's radius. That Iron should give the larger value was to be expected, for the assumption that the envelope has vanished is less nearly true for it than for Platinum, as their relative compressibilities show. Allowing, then, for the presence of some envelope even in metallic Platinum, we may take the radius of the magneton to be about 1.5×10^{-9} cm. This is only about one-tenth of the radius of the total atomic space usually found in a solid or liquid, where the envelope may occupy a large part of it.[1]

Now since the velocity at the circumference of the magneton has been assumed equal to c (the velocity of light), we have for the moment of the magneton:

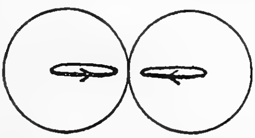
$$
\begin{aligned}
\text{Moment} &= \text{area} \times \text{current} \\
&= \pi r^2 \times \frac{ec}{2\pi r} \\
&= \frac{rec}{2} \\
&= (1.5 \times 10^{-9}) \times (1.55 \times 10^{-20}) \times (3 \times 10^{10}) \div 2 \\
&= 3.5 \times 10^{-19} \text{ E. M. U.}
\end{aligned}
$$

[1] The radii of some atomic spaces may be given for comparison with those of the corresponding positive spheres, and that of the magneton. It should be noticed that the values of ($R'-R$) got from the table below give the volume of the envelope.

	R' (of atomic space)	R (of positive sphere)	r (of magneton)
H (solid)	1.7×10^{-8}	$.36 \times 10^{-8}$	$.15 \times 10^{-8}$
He (liquid)	2.2 "	.72 "	
C (solid)	1.1 "	.83 "	
O "	1.7 "	.85 "	
Na "	2.1 "	.91 "	
K "	2.6 "	.98 "	
Fe "	1.4 "	1.1 "	
Pt "	1.5 "	1.5 "	

The values given for R must all be too great because they are derived from the assumption that the envelope has quite disappeared in solid Platinum. In the case of H there is also a factor that would tend to make it too small—the lack of internal magnetic compression has been left out of account. In a subsequent paper, evidence will be adduced from the phenomena of electrolytic dissociation to show that the positive sphere of this atom has a radius of about $.50 \times 10^{-8}$.

In comparison with this we have for the moment of the Iron atom in the metal at saturation the value 2×10^{-20} only, and for the Iron atom in salts or for the Oxygen atom considerably smaller values. Also the moment of Weiss' magneton is 1.85×10^{-21}.

If, therefore, the magneton under discussion were required to correspond to an empirical unit of magnetic moment, as does Weiss' magneton, this result would be fatal to it: but with magnetons which are movable current circuits, the result is exactly what we would look for. On the present theory, it can be definitely affirmed that no atom, however many magnetons it contains, can have a moment greater than that of one magneton, and that the moment of most atoms will be very much less than this, because the force between the magnetons in an atom will always tend to orient them so as to make their resultant moment zero. The group of eight, with a very low magnetic energy, has no moment: the free, or valence, magnetons will always tend to lie in configurations of no moment; and indeed the only atoms that could be imagined to have a moment as great as that of the magneton are the atoms H, Li, Na, K, Rb, Cs, of the constitution $n\gamma + 1$, which contain only one valence magneton each. Further, what has just been said applies only to isolated atoms: in polyatomic molecules, or in the liquid or solid state, the moment of the atom will be still further reduced by the mutual actions of the magnetons of different atoms. To take an illustration, the isolated H atom should have the moment of one magneton, but the H_2 molecule can have the configuration , with no moment, while in HCl or HI all the magnetons are in groups of eight (for most of the time). Nothing, I believe, is known about the magnetic properties of any substances as monatomic gases except Helium and Argon (see §2), and perhaps Mercury. The investigation of them would present exceptional difficulties, but it would be a valuable test of much of this magneton theory, and will be undertaken at the earliest opportunity.

Meanwhile, the view here taken that the moment of the Iron atom, even, is a comparatively small difference effect has everything to recommend it. The great dependence of the moment upon temperature and upon the mode of chemical combination makes it clear that it is a very delicately balanced effect which is due beyond all doubt to certain favorable configurations of those portions of the atom which are responsible for the forces exerted on other atoms. It is most

unlikely that it could be due to any simple rectilinear arrangement of unit magnets or current circuits, such as N|S—N|S—N|S—N|S, etc., which is the only conception of the atom's structure that could give Weiss' magneton any structural significance.

§18. The Possibility of Detecting the Magneton Directly: The Heat of Dissociation of Hydrogen

That the magneton has never yet been detected directly by its magnetic moment is not at all surprising, for a consideration of the possibilities shows that this is either beyond or just at the limit of the present experimental resources.

First, in kathode rays: We have for the force which produces the familiar deflection across the lines of magnetic force:

$$\begin{aligned} Hev &= H \times 1.57 \times 10^{-20} \times 3 \times 10^{9} \\ &= H \times 5 \times 10^{-11} \text{ dynes.} \end{aligned}$$

Now the force on the magneton due to any non-uniformity in a magnetic field through which it passes is

$$\frac{dH}{ds} \cdot M = \frac{dH}{ds} \times 3.5 \times 10^{-19} \text{ dynes.}$$

Seeing that in experiments on kathode rays, H has been perhaps 500 gauss, and that a gradient $\frac{dH}{ds}$ can scarcely be made to exceed 50,000 gauss per cm. by any means whatever, it is obvious that the second force is too small ever to be detected by any deflection of kathode rays.

Another line of attack is more promising. If the electron has a magnetic moment, we may expect to be able to increase the concentration of electrons in an earthed conductor by setting up a magnetic field over it. In this case we can calculate the potential reached (V) by equating the electric work gained with the magnetic work lost for the movement of each magneton.

$$\frac{Ve}{2} = HM.$$

$$\begin{aligned} \therefore V &= H \times \frac{2 \times 3.5 \times 10^{-19}}{1.57 \times 10^{-20}} \\ &= H \times 45 \text{ E. M. U.} \\ &= H \times 4.5 \times 10^{-7} \text{ volts.} \end{aligned}$$

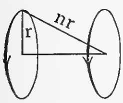
Now over a conductor of such a size and situation as to have a reasonably great capacity (such as 10 E. S. U.), it is difficult to set up a magnetic field of more than 1,000 gauss. Assuming this field,

we have $V = 4.5 \times 10^{-4}$ volts. Complications apart, this is within the range of the most sensitive electrometers, but a practical study of the problem shows many difficulties. However, experiments on this matter are in progress.

Langmuir's recent work on atomic Hydrogen opens up another line of attack, for the H atom should have the same moment as one magneton. Langmuir found that these atoms could be made to travel some distance from the point of their dissociation without recombining, and could then increase the resistance of a coil of fine platinum wire in which they dissolved. The present author proposes to study the effect of a non-uniform magnetic field on their movements.

Although there has not as yet been any direct detection of the moment of the magneton, it is possible to make a rough calculation of the heat of dissociation of the H_2 molecule from the assumptions of this theory.

In §5 was given a diagrammatic representation of the H_2 molecule. Using the original assumption that the radius of the magneton is about half that of the H atom, we see that the two magnetons in this molecule are about twice the length of their radius (r) apart.



Let the distance from the circumference of one magneton to the center of the other be nr.

Now the field due to one magneton, at a point lying on its axis and distant by nr from its circumference, is

$$2\pi \cdot \frac{M}{\pi r^2} \cdot \frac{r^2}{(nr)^3} = \frac{2M}{n^3 r^3}.$$

Hence the magnetic work done in bringing the other magneton from infinity up to this point is roughly

$$\frac{2M^2}{n^3 r^3} = \frac{2 \times (3.5)^2 \times 10^{-38}}{n^3 \times (1.5)^3 \times 10^{-27}}$$

$$= \frac{7.5 \times 10^{-11}}{n^3} \text{ ergs,}$$

and for a gram-atom of Hydrogen this amounts to

$$\frac{4.5 \times 10^{13}}{n^3} \text{ ergs.}$$

Substituting the values 1, 2 (most probable), and 3 for n, we have

$$4.5 \times 10^{13}, \qquad 5.6 \times 10^{12}, \qquad 1.7 \times 10^{12} \text{ ergs}$$

for the heat of dissociation. Now Langmuir's calculations from experiment give as the probable value about 77,000 cal.[1] or

$$3.2 \times 10^{12} \text{ ergs.}$$

[1]Phil. Mag., 27, 188, 1914.

If it had been assumed that v for the magneton was about $.01 \times c$ (which is the sort of velocity usually attributed to the electron in orbital motion), the calculated heat of dissociation would have been 10,000 times less, and even if the radius of the magneton were supposed to be as great as that of the whole atom, the value would only be increased 10 times. This is strong support for the assumption $v=c$, which was made originally on more general grounds.

In the foregoing calculation the electric work required to draw the magnetons from the centers of their atoms, and the elastic work required to compress the envelopes of the atoms, have been neglected. These would obviously be smaller quantities, as they are associated with secondary effects, and could not affect the order of magnitude of the result. Their effect would, in fact, be to diminish the work required to separate the two atoms, and so, probably, to bring the calculated value into even better agreement with the actual value. It should also be borne in mind that the calculation has been made for the more improbable of the two conceivable configurations of the molecule (see §§ 5, 20); but it is certain that the resultant forces would be very much the same in the two cases, although the mathematics involved would be more intricate for the other configuration.

§19. The Magnetic Properties of Matter

A brief survey of the present state of our understanding of magnetism may be included at this point.

A theory giving a complete account of magnetic phenomena must, in its final deductive aspect, proceed in certain logical steps. First it must provide a sub-atomic mechanism that would actually be expected to produce, in a general way, the external magnetic phenomena that are observed for gross matter. Secondly, it must include a fairly detailed view of the structures of the different atoms, so as to explain their different magnetic properties. And lastly, the combining properties which it gives to the atoms must be such that the explanation can be extended to the magnetic properties of all kinds of molecules and solid aggregates of atoms and molecules.

Hitherto no theory of magnetism has attempted to go further than the first step, and I have shown in §2 how incomplete even that has been. The present theory, on the one hand, is of so definite and far-reaching a character that it is able, in a certain sense, to cover the whole ground. It is true that very little is known as yet about the magnetic properties of the atoms themselves, but what is known is explained by it (see §2, and below, for Helium and Argon).

Again, while the theory gives a good account of the magnetic changes that may be expected to accompany chemical changes, it has up to the present yielded very little in explanation of ferromagnetism. This phenomenon, after all, is generally recognized to be due to a fortuitous alignment, which can occur only in favorable circumstances, of the magnetic effects of separate atoms or molecules; and the problems connected with it, when regarded from the present fundamental point of view, are of a higher order of difficulty altogether than the problems of paramagnetism: the two stand in much the same mutual relation as the problem of the structure of a solid bears to that of a simple molecule. This has been emphasized by Curie and Weiss.

In the study of the magnetic properties of gross matter, the most important step in recent years is recognized to have been the formulation of Curie's laws: 1. *Ferromagnetic* substances have a transition point, at different temperatures for different substances, at which they lose most of their moment and become merely paramagnetic (the "Curie point"). This transition is compared to that between a liquid and its vapor. The moment of a ferromagnetic substance is not proportional to the field intensity, but reaches a maximum value, called the saturation value. (These things had long been appreciated in the case of Iron.) 2. The susceptibility (κ) of a *paramagnetic* substance is inversely proportional to the absolute temperature (T) —so that κT is a constant (the "Curie constant"): κ is independent of the field intensity. 3. The susceptibility of a diamagnetic substance is independent of both the temperature and the field intensity.

These results led to a consistent theory of "external" magnetic phenomena based on Langevin's electronic orbit as the unit upon which the field acts. Diamagnetism, due to currents induced in these orbits, would be expected to be independent of the temperature, because for other reasons, such as the constancy of wave-lengths of spectrum lines, the interior of an atom is supposed to be not much affected by atomic collisions. Paramagnetism is obtained when the atoms of a substance have a magnetic moment great enough to outweigh the ever present diamagnetic effect: molecular vibrations are bound to interfere with the orientation of these atoms by the external field, and in this way the temperature relation found by Curie has been explained by Langevin (*loc. cit.*, §2). Ferromagnetism, only possible below a critical temperature, is the state in which the disturbing effect of the vibrations is overcome and the atoms align them-

selves definitely, in greater or less numbers according to the strength of the external field, until at saturation they are all aligned.

The relation κT = const. for paramagnetic substances was found by Curie to hold for Oxygen, Palladium, and certain salts, and over a certain range of temperature for Magnetite; but it has been amply demonstrated that the law is not of universal application. Weiss and Kamerlingh Onnes have shown (Journal de Physique, 1910) that Iron, Nickel, and Cobalt are exceptions; and that the susceptibilities of Vanadium, Chromium, and Manganese are not increased by cooling to the boiling point of Hydrogen (14° abs.), whereas according to Curie's law they should increase about twentyfold. It is remarkable also that, even down to such low temperatures, no transition into a ferromagnetic state is observed in these elements. Again, the work of Honda (*loc. infra*) has shown that there is a class of substances whose susceptibilities even increase with rise of temperature.

This last effect is to be expected from the magneton theory, because sometimes magnetons which at lower temperatures are held quasi-rigid by interatomic forces might at higher temperatures be more free to add to the paramagnetic effect. We may say, then, that the occurrence of molecular collisions will tend to make paramagnetism obey Curie's law, but that the action of intermolecular and interatomic forces would be expected to enhance paramagnetism as the temperature rises, although the latter effect would not be marked except during a change of molecular complexity, such as occurs during gaseous dissociation and to a less extent during fusion and volatilization (see §22).

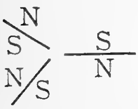
The law for diamagnetism—that it is independent of temperature—is not universally true either. As a striking example of this, Bismuth becomes less diamagnetic as the temperature rises, and at the melting point the change is so great that liquid Bismuth is the least diamagnetic substance known.

These departures from Curie's laws will seem less anomalous after considering the vivid picture of the distribution of magnetic forces within atoms, molecules, and lumps of solid matter, which this theory affords.

In beginning to apply the theory, we can see at once that the stable group of eight magnetons (§6) is an almost ideally diamagnetic system. It has no intrinsic magnetic moment, and on account of its low magnetic energy is not easily given one. The way in which an external field would tend to distort the group is well shown in configs. 1, 3, 3*a* on plate 2 (§6): this illustrates the paramagnetic part

of the behavior of the group. But when we remember that the earth's field is for that model relatively very much stronger than any possible field can be for actual atoms, it is easy to see that the paramagnetic effect would be slight.

The presence of free magnetons, on the other hand, would make for paramagnetism; but would not necessarily succeed in producing it in all cases, for even "free" magnetons may form fairly stable groupings of no intrinsic moment, such as $\frac{\mathrm{N}}{\mathrm{S}}\ \frac{\mathrm{S}}{\mathrm{N}}$ for two,



for three, and so on. It must always be borne in mind that the observed magnetic effect is the difference between the separate paramagnetic and diamagnetic effects, as Langevin points out; and unless it is large in proportion to the number of magnetons in the atom, it gives very little clue to the absolute value of either of them. (This explains those cases where diamagnetism seems to be dependent upon temperature.) These considerations will make it clear that, while any obvious contradictions will be evidence against the theory, not too much in the way of positive correlation of magneton constitutions with magnetic phenomena must be expected from it at this first attempt.

There follows now a set of references to the investigations from which I have collected data, with the letters (in parentheses) by which they will be referred to in what follows:

(Q) *Quincke:* Gases at pressures up to 40 atm.: method of the effect of a magnetic field on gas-liquid surfaces (Wied. Ann., 34, 401, 1888).

(C) *P. Curie:* Effect of temperature on the magnetic properties of typical substances (Ann. de Chim. et de Phys., 1895).

(M) *Stephan Meyer:* Magnetic properties of the elements, and periodicity in them (Wied. Ann., 68, 325, 1899). A survey of all classes of inorganic compounds in search of additive relations (Wied. Ann., 69, 236, 1899; Ann. der Phys., [3] 1, 189, 1900).

(L) *Liebknecht and Wills:* Cr, Mn, Fe, Co, Ni, Cu, in their salts (Ann. der Phys., [3] 1, 177, 1900); *du Bois and Liebknecht:* Rare-earth elements in their chlorides (Ann. der Phys., [3] 1, 189, 1900).

(T) *P. Tanzler:* Susceptibilities of He, A, air, compressed in glass bulbs: method of moment in a non-uniform field (Ann. der Phys., [5] 24, 931, 1907).

(U) *Urbain and Jantzsch:* Rare-earth oxides (C. R., 147, 1286, 1908).

(P) *P. Pascal:* The susceptibilities of many non-metallic elements and easily liquefiable gases—all diamagnetic: also carbon compounds studied, and additive relations found, but constitutive influences are very marked—all diamagnetic (Ann. de Chim. et de Phys., 19, 5, 1908). The magnetism of V, Cr, Mn, Fe, in relation to their state of combination (C. R., 147, 742, 1908).

(B) *Bernstein:* H_2 and Cl_2 gases at 1 atm. (diss: Halle, 1909). I am unable to find out his method, or whether his results are reliable.

(H) *K. Honda:* The specific susceptibilities of the elements, and their temperature coefficients, with special allowance made for ferrous impurities in the specimens used (Ann. der Phys., 32, 1027, 1910).

(W) *P. Weiss and co-workers:* (Papers in C. R., 150; 152; Jour. de Phys., [4] 9, 1910). A summary of his whole work (Jour. de Phys., [5] 1, 900, 965, 1911).

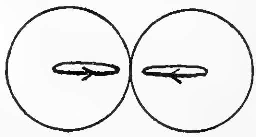
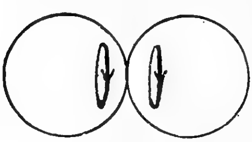
(F) *E. Faytis:* Complex salts, especially cobaltammines, are almost always diamagnetic: molecular paramagnetism is greater in hydrated than in anhydrous salts (C. R., 152, 708, 1911).

(O) *A. E. Oxley:* Iron and Nickel carbonyls and $K_4Fe(CN)_6$ are diamagnetic; $K_3Fe(CN)_6$ is slightly paramagnetic (Proc. Camb. Phil. Soc., 17, 450, 1914).

In all cases where the authors give specific susceptibilities, the atomic or molecular values have been calculated for use here, except where the contrary is stated: for uniformity all values are expressed as $x \times 10^{-6}$ and the 10^{-6} factor is dropped.

§20. The Magnetic Properties of the Elements

Turning to the structures derived for the atoms in Part II, we see that the atoms of the inactive rare gases should be the most strongly diamagnetic of all atoms. That this is so, with the barely possible exception of H in the H_2 molecule (see below), may be seen from the accompanying table. Comparing atomic susceptibilities, we find that Helium (γ) is more diamagnetic than any element (of another group) lighter than *solid* Zirconium ($5\gamma+4$), while Argon (3γ) is second only to *solid* Bismuth ($10\gamma+5$). This is especially significant because the gaseous state, particularly the monatomic gaseous state, must be less favorable to diamagnetism than the liquid or solid state, for it allows any "free" magnetons to have their fullest freedom (see §22).

The case of the H_2 molecule is difficult to deal with. The two possible configurations described in §5 would correspond to very different magnetic properties.  would be expected to be diamagnetic, as it has no natural moment, but  strongly paramagnetic. On account of the

		γ	2γ	$3\gamma \ldots 4\gamma$	$5\gamma \ldots 6\gamma$	$7\gamma \ldots 8\gamma$		11γ
		He —38.8 (T)	Ne	A — 212 (T)	Kr	Xe	+	Nt
+1 ……	H —?	Li + 2.7	Na +11.7	K + 15.6	Rb + 47.6	Cs	+	—
+2 ……	……	Be + 7.1 (M)	Mg +13.3	Ca	Sr	Ba	+	Ra
+3 ……	……	B — 7.8	Al +17.6	Sc — x (M)	Y	La —x (U)	+	—
+4 ……	……	C — 5.9 (diamond) —24	Si — 3.7	Ti + 90 (M)	Zr — 40.8	Ce	+	Th +42
$+\overline{5}$ ……	……	……	……	V + 77	Nb +132	+	Ta +168	—
$+\overline{6}$ ……	……	……	……	Cr + 193	Mo + 3.8	+	W + 16	U +215
$+\overline{7}$ ……	……	……	……	Mn +1000 (?)	—	+	—	—
$+\overline{8}$ ……	……	……	……	Fe, Co, Ni Ferro-magnetic	Ru + 57, Rh +113, Pd +619	+, +, + Almost all strongly paramagnetic (L, U).	Os +7.8, Ir + 29, Pt +209	
$+\overline{9}$ ↓ $\gamma+1$ ……	……	……	……	Cu — 5.5	Ag — 22	+	Au — 30	
$+\overline{10}$ ↓ $\gamma+2$ ……	……	……	……	Zn — 10.1	Cd — 19	+	Hg — 38	
$+\overline{11}$ ↓ $\gamma+3$ ……	……	……	……	Ga — x (M)	In — 11	+	Tl — 61	
+4 ……	……	……	……	Ge — x (M)	Sn + 3 (cryst.) — 42 (grey)	+	Pb — 25	
+5 ……	……	N + 10.5 (Q)	P —19.2	As — 23.2	Sb —114	+	Bi —291	
+6 ……	……	O +1840 (C) +1367 (T)	S —15.4	Se — 25.3	Te — 41	+	—	
+7 ……	……	F	Cl —20.9 (P)	Br — 32	I — 46	+	—	

(Except where otherwise stated, the values are got from the work of Honda (*loc. cit.*). Many of Meyer's results must have been vitiated by ferrous impurities; *e. g.*, he gives +47 for B, +13,000 for La, +1,600 for Th: all such values have been omitted.)

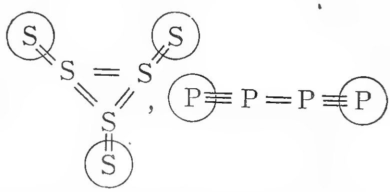
number of factors in the problem it is hard to say which configuration to predict from the original assumptions. The two factors of magnetic attraction between the magnetons and electric attraction between each magneton and its positive sphere would make for the first configuration, but the electric repulsion between the magnetons for the second.

Nor do there seem to be any reliable data for the susceptibility of this gas, the low density of which makes a determination very difficult. Quincke (*loc. cit.*) obtained for the susceptibility per cc. the value $+.008$ at 1 atm., but $\pm.000$ at 40 atm. The only other determination available seems to be that by Bernstein (*loc. cit.*), who gets the value $-.005$ for the specific susceptibility at 1 atm., which corresponds to an atomic susceptibility of -50 ($\times 10^{-6}$). But his only other result (according to Landolt's tables)—the value -78 for the atomic susceptibility of gaseous Chlorine at 1 atm.—is nearly four times as great as Pascal's more reliable value (-20.9) for Chlorine in the liquid state, where the element certainly could not be *less* diamagnetic (see §22). It seems, therefore, that the H_2 molecule, if diamagnetic, is less so, and probably much less so, than two He atoms.

But the solid alkali metals, whose atoms, like H atoms, contain only one valence magneton, are slightly paramagnetic. In their case, however, one of the factors that made for the diamagnetic configuration in the H_2 molecule—the attraction of the positive spheres for the magnetons—is obviously modified by the presence of the groups of eight in such a way as to make the diamagnetic configuration of the valence magnetons less stable than in the case of H_2: also, the vibration of the neighboring atoms would tend to prevent the formation of a stable positive bond such as the H_2 molecule possesses, thus leaving the magnetons freer than they could be in the latter, which, though isolated, has its two atoms firmly united together.

With regard to periodicity in magnetic properties, the first short period of the Periodic Scheme is exceptional in some respects, but as we pass along the second short period we find that the presence of 1, 2, and 3 valence magnetons makes the atom more and more paramagnetic, though not in proportion to their number. The absence of proportionality may be attributed partly to the superimposed diamagnetic effect of the two groups of eight, which is probably similar to that of the Neon atom (2γ) in all three; and partly to the interference of the valence magnetons, in the same and in contiguous atoms, with one another's freedom. The intra-atomic part of this interference culminates towards the end of the period in the tendency

to form a new group of eight that is characteristic of the "negative" atoms: this destroys the paramagnetism. If Phosphorus, Sulphur, or Chlorine atoms were isolated, they might be found to be paramagnetic (it may be possible to test this with monatomic Iodine gas); but the ordinary state of Chlorine is (Cl⫟Cl), in which all the magnetons are bound for most of the time (see §9), while the complexity of the gaseous molecules of Sulphur and Phosphorus leaves little doubt that most of the valence magnetons are in groups of eight or double positive bonds [1] as in

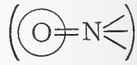
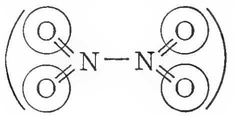
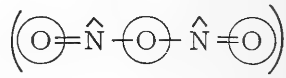
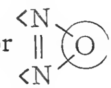
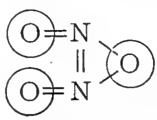


etc.

In the first short period, the diamagnetism of Boron $(\gamma+3)$ is explainable on the principles already set forth; and the striking feature is the strong paramagnetism of the Oxygen $(\gamma+6)$ molecule as compared with the comparative magnetic inertness of the Nitrogen $(\gamma+5)$ molecule. The only available determinations for Nitrogen appear to be Quincke's, who gives for the susceptibility per cc. $+.001$ at 1 atm., and $+.04$ at 40 atm.: these are evidently more reliable than his values for Hydrogen, but there is the possibility here of contamination with Oxygen.

As for Oxygen, since in oxides, such as $\begin{matrix}H\diagdown \\ H\diagup\end{matrix}(O)$, $Ca\ne(O)$, it is invariably diamagnetic, its paramagnetism in the molecular state has led J. J. Thomson and others to suppose that one of the two atoms is acting "positively." This, according to the present theory, would be represented by $(O)\!\!\ne\!\hat{\hat{O}}$, which formula has already been given in §9: there it was supposed that the molecule had another phase containing the double negative bond: $(O\ne O)$. If the existence of the first phase is the true explanation of the paramagnetism of the O_2 molecule, we should expect the N_2 molecule, $(N)\!\equiv\!\hat{N}$, to be para-

[1] A double positive bond is expected to have no magnetic moment, as will be shown in a future paper: as we have seen for the H_2 molecule, a single positive bond need have none.

magnetic also, unless, as is possible, it is easier, in the presence of a group of eight, for two magnetons to form a group of no moment than for a larger number (see arguments at the end of §12). A diatomic molecule very similar in constitution to N_2 and O_2 is NO : this is strongly paramagnetic (Q); and, contrary to the usual impression, the paramagnetism must lie in the unsaturated N atom rather than in the O atom, according to the present view. Liquid N_2O_4  and N_2O_3  are diamagnetic (P), but liquid Oxygen retains its paramagnetism almost unaltered (K. Onnes). N_2O, whose constitution is possibly , or , is according to Quincke slightly paramagnetic. Possibly N_2O_3 has a more condensed structure than has just been written, *e. g.*, , which would accord better with its diamagnetism. From all this, we may see the possibility of diatomic sulphur vapor being paramagnetic, and we would expect NO_2 to be less diamagnetic than N_2O_4 or even paramagnetic: these points have not as yet been investigated experimentally.

Turning to the long periods, we find that the assumption made on chemical grounds about the absence of a tendency to form the group of eight is justified in the magnetic properties of the transition metals. Unlike P ($2\gamma+5$), S ($2\gamma+6$), Cl ($2\gamma+7$), A (3γ), which are all diamagnetic, V ($3\gamma+5$), Cr ($3\gamma+6$), Mn ($3\gamma+7$), (Fe Co Ni) ($3\gamma+8$) are all paramagnetic, quite apart from ferromagnetism. The same is true of the corresponding series in the second and third long periods: Nb, Mo, ——, (Ru Rh Pd); and Ta, W, ——, (Os Ir Pt). The rare-earth elements, which precede Tantalum, and whose structures have been compared with those of the elements just mentioned (§13), are also strongly paramagnetic, some of their salts being even more so than Iron salts.

In the second half of the long periods we find that the elements are all diamagnetic. For the first three of them,

$$
\begin{array}{ccc}
\text{Cu} & \text{Zn} & \text{Ga} \\
3\gamma+\overline{9} & 3\gamma+\overline{10} & [3\gamma+\overline{11}], \\
\downarrow\uparrow & \downarrow\uparrow & \downarrow\uparrow \\
[4\gamma+1] & 4\gamma+2 & 4\gamma+3
\end{array}
$$

this is somewhat surprising, although their 4γ phases, certainly, would not be expected to be particularly magnetic. We may note, however, that Cu and Zn are much less diamagnetic than elements which are expected to be so; *e. g.*, A, Bi, Cl, Br, etc. As, Se, Br and Sb, Te, I are diamagnetic for the same reasons as P, S, and Cl are.

As regards the cases just noted where diamagnetism is found instead of the paramagnetism at first expected, we may say that, as already indicated, the interference of free magnetons with one another's orientation, both in the same atom and in neighboring atoms, holds out a possibility of a sufficient explanation, although the rules governing this interference must be very complex and are at present obscure. More definite corroboration of the principles of the magneton theory is got from a consideration of certain compounds, which follows now.

§21. The Magnetic Properties of Compounds

The typical saturated compound has no free magnetons; and of most saturated inorganic molecules we can say more: all the valence magnetons of the constituent atoms have gone to make up groups of eight. Thus it is that, while O_2 is paramagnetic and the metals Li, Na, K, Be, Mg, Ca, Sr (?), Ba are all paramagnetic, the oxides and chlorides of these metals, such as $\text{Mg}{=}\text{O}$, $\text{K}{-}\text{Cl}$, are without exception diamagnetic.

The ordinary salts of Fe, Ni, Co, which according to the present views must contain free magnetons, are strongly paramagnetic, while the complex Fe salts and the "cobaltammines," in which, presumably, these free magnetons are bound, are very slightly paramagnetic, or, more often, diamagnetic.

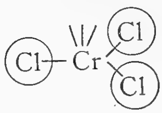
A table of data illustrating these points and the arguments which follow is given herewith. It was found necessary to supplement the available data by a few determinations for the complex compounds of Cu, Ag, Au, Zn, Hg: the rough method used gave results which agreed with known values (in the case of other substances) to 10 per cent or so.

Group	Element and valence	Form	Atomic suscept.	No. of free magnetons
V	V^0	metal	+77.8 (H)	$\bar{5}$
	V^{II}	VCl_2	+1390 (P)	$\bar{3}$
	V^{III}	$(V_2O_2)SO_4$	+1150 (P)	$\bar{2}$
	V^{IV}	V_2O_4	+660 (P)	$\bar{1}$
	V^V	$NaVO_3$	—300 (P)	0
VI	Cr^0	metal	+193 (H)	$\bar{6}$
	Cr^{III}	alum	+6290 (P)	$\bar{3}$
		$CrCl_3$	+6250 (Weber)	
	Cr^{VI}	CrO_3	— 5.0 (P)	0
		$K_2Cr_2O_7$	+18.5	
	U^0	metal	+215 (H)	$\bar{6}$
	U^{IV}	$U(SO_4)_2$	+3200 (P)	$\bar{2}$
	U^{VI}	$(UO_2)SO_4$	—56 (P)	0
VII	Mn^0	metal	+600 to 2000 (H)	$\bar{7}$
	Mn^{II}	$MnSO_4$	+15000 (P)	$\bar{5}$
	Mn^{III}	$MnPO_4$	+10840 (Weber)	4
	Mn^{VII}	$KMnO_4$	+255 (P)	0
		$KMnO_4$ (solid)	+33	
VIII	Fe^0	metal	ferromagnetic	$\bar{8}$
	Fe^{II}	salts	very strongly paramagnetic	$\bar{6}$
	Fe^{III}	salts		$\bar{5}$
	Fe^{VI}	ferrates	diamagnetic	2
	$Fe^{VI+?}$	complex salts	diamagnetic	0 (?)
	Similar relations for Co and Ni.			

Group	Element and valence	Form	Atomic suscept.	No. of free magnetons
I B	Cu^0	metal	—5.5 (H)	$\bar{9} \rightleftharpoons \gamma+1$
	Cu^I	CuCl	—26	$\bar{8} \rightleftharpoons \gamma$
		CuCN	—43	
	$Cu^{I+?}$	$KCu(CN)_2$	—80	$<\bar{8}$ (?)
	Cu^{II}	$CuCl_2$	+1000	$\bar{7}$
		$CuCrO_4$	+1070	
		$CuSO_4$	+1730	
		$Cu(NH_3)_4SO_4 \cdot H_2O$	+1750	
		$CuAc_2$	+ 550	
	Ag^0	metal	—22 (H)	$\bar{9} \rightleftharpoons \gamma+1$
	Ag^I	AgCN	—51	$\bar{8} \rightleftharpoons \gamma$
		$AgNO_3$	—38	
	$Ag^{I+?}$	$KAg(CN)_2$	—64	$<\bar{8}$ (?)
	Au^0	metal	—30 (H)	$\bar{9} \rightleftharpoons \gamma+1$
	Au^I	AuBr	—27	$\bar{8} \rightleftharpoons \gamma$
	$Au^{III(?)}$	$AuBr_3$	—70	$\bar{6}$ (?)
II B	Zn^0	metal	—10 (H)	$\overline{10} \rightleftharpoons \gamma+2$
	Zn^{II}	$Zn(NO_3)_2 \cdot 6H_2O$	—128	$\bar{8} \rightleftharpoons \gamma$
		$Zn(CN)_2$	— 67	
	$Zn^{II+?}$	$K_2Zn(CN)_4$	—102	$<\bar{8}$ (?)
	Hg^0	metal	— 38 (H)	$\overline{10} \rightleftharpoons \gamma+2$
	$Hg^{I(?)}$	Hg_2Cl_2	— 76	$\bar{9} \rightleftharpoons \gamma+1$ or $\bar{8} \rightleftharpoons \gamma$
		$Hg_2(NO_3)_2$	— 73	
	Hg^{II}	$HgCl_2$	— 87	$\bar{8} \rightleftharpoons \gamma$
		$Hg(NO_3)_2$	— 93	
		$Hg(CN)_2$	—113	
	$Hg^{II+?}$	K_2HgI_4	paramagnetic	$<\bar{8}$ (?)

(Pascal's values (P) are for solutions. All values have been multiplied by 10^6.)

In comparing these values two things should be borne in mind: first, that susceptibilities of paramagnetic substances in solution are in general greater than for the undissolved substances (Pascal's values under (P) are for solutions); and second, the values obtained for diamagnetic salts have little significance for the metal atoms that are in them except to show that they are not decidedly paramagnetic, for the acid radicles themselves are diamagnetic.

In the table I have given space to the compounds of the transition metals of groups V, VI, VII, VIII, I B, II B only, because there the relations are much more complex. We may notice first that the free elements V, Cr, Mn, are much less paramagnetic than their salts. This, I think, is due to the same cause as the general rule that these salts are more paramagnetic when hydrated than when anhydrous (F), and still more so in solution. If, as this theory would indicate, paramagnetism is an effect of free magnetons in the metal atom, then the farther removed from one another these atoms are, the more free from constraint must be their magnetons (as many as remain free). In metallic Chromium, for example, the six valence magnetons are used to a considerable extent, as the high melting point indicates, in binding the atoms together by positive bonds (not so diamagnetic an arrangement, however, as if it involved groups of eight). In  it is true that only three free magnetons are left, but these are likely to be more free from the influence of other Cr atoms than can be the case in metallic Chromium. In hydrated $CrCl_3$ they are still more free, not being used up in combining with H_2O molecules as might at first be suspected, for since H_2O is most of the time in the "saturated" phase (see §9) it would not have much attraction for free magnetons. For other facts illustrating this general principle see §23.

Turning to the relations between the compounds of these metals of groups V-VIII, we see that, if the uncombined metals are excepted, the paramagnetism runs parallel with the number of free valences or magnetons, until in the saturated compounds it vanishes ($NaVO_3$, CrO_3), or becomes very small ($KMnO_4$). This relation has been roughly indicated by Pascal (*loc. cit.*).

In the transition metals of groups I B and II B, however, we find a different set of relations. We have seen that a great deal is explained by the tautomerism which naturally falls to the lot of these elements (see table of Periodic Scheme, §7). The very striking fact that

Copper, while diamagnetic as metal or in cuprous compounds, is paramagnetic in cupric compounds, is attributable to this tautomerism also.

In monovalent Cu, Ag, Au, and in the salts of Zn, Cd, Hg, there are 8 free magnetons left, and the tautomerism $\bar{8} \rightleftharpoons \gamma$ is still possible: therefore we expect, and find, diamagnetism. But in bivalent Cu, where only $\bar{7}$ are left, this tautomerism is no longer possible, and the salts are strongly paramagnetic, as this theory would predict. Another prediction—that AuBr ($\bar{8} \rightleftharpoons \gamma$) should be diamagnetic, and $AuBr_3$ ($\bar{6}$) paramagnetic—is not so successful, for both are diamagnetic: but the obvious refuge from the difficulty will suggest itself. Compounds of bivalent or trivalent Silver are of course not available for comparison.

The complex salts of these metals were also studied, in the hope of getting results analogous to the well-known relations for Fe and Co (F). Bivalent Cu was obviously the best point of attack, but the most stable complex cupric salt obtainable seems to be $Cu(NH_3)_4SO_4 \cdot H_2O$, and this is still very paramagnetic: a cupricyanide ($K_2Cu(CN)_4$), if it were stable, might be expected to show a much diminished paramagnetism, just as ferri-cyanides do. The complex cyanides derived from salts which are diamagnetic already, *e. g.*, those of Cu^I ($\bar{8} \rightleftharpoons \gamma$), Ag^I ($\bar{8} \rightleftharpoons \gamma$), Zn^{II} ($\bar{8} \rightleftharpoons \gamma$), are all diamagnetic, although it is hard to see how, in a small complex molecule like $KAg(CN)_2$, all the 8 free magnetons of the monovalent Ag atom can be involved. However, the effect we should be inclined to look for in such cases—a paramagnetism—has been observed in one compound at least. Pascal found that the salt K_2HgI_4 in solution is paramagnetic; so it seems that not all of the free magnetons of bivalent mercury, Hg^{II} ($\bar{8} \rightleftharpoons \gamma$), are involved in this case.

§22. THE DEPENDENCE OF MAGNETISM UPON TEMPERATURE AND PHYSICAL STATE

In the preceding sections (esp. §19), the influence of neighboring atoms and molecules on one another's magnetism has been continually spoken of, and it has been brought out in a general way that this may be expected to diminish a resultant paramagnetism or increase a resultant diamagnetism. A summary of the experimental evidence on this point will now be given; and in considering this, it should be remembered that the influence of one atom or molecule upon another becomes diminished as the temperature rises.

1. For the paramagnetism of a metallic atom we have the following relations:

Salts in solution>Hydrated salts>Anhydrous salts>Free metal.

This is true for V, Cr, or Mn. In the case of ferromagnetic metals, the last step in the series does not hold, of course, except above the Curie point. These relations have not been established with any great completeness, and possibly some exceptions exist.

2. In mixtures of liquid Oxygen and Nitrogen, the molecular susceptibility of the Oxygen becomes greater as its concentration becomes less (K. Onnes).

3. Contrary to Curie's law, almost half of the paramagnetic elements become increasingly paramagnetic as the temperature rises (H). This can only be due to increased freedom acquired by the magnetons that are responsible for the forces between atoms, as explained in §19.

4. Most of the diamagnetic solid elements (*e. g.*, Bi, Sb, Pb, Tl, Te, In, Cu) become less diamagnetic as the temperature is raised (H), the change being in some cases especially marked at the melting point, after which a further rise in temperature does not usually alter the magnetic properties. Evidently we have here cases of complex molecules which become less stable as the melting point is approached, and which at that point are suddenly broken down into the atoms or molecules that are stable in the liquid phase. From the magneton theory we should expect this process to be accompanied by the magnetic changes that are observed. Those elements which do not show this effect are for the most part elements of lower atomic weight which are known to give stable complex molecules persisting in the liquid and even in the gaseous state (*e. g.*, P, As, S, Se): these, therefore, act more like the substances described under the next heading (5). A very striking example of the effect of fusion is given by the alloy $FeZn_{10}$; when solid this is non-magnetic, when liquid it is very strongly magnetic: a comparison of the susceptibility of this alloy with that of the Iron atom in salts would be of great interest, but appears not to have been made. An example of the effect of dissociation by dilution is given by solutions of Bismuth in mercury, which when very dilute are less diamagnetic than pure mercury: this must be due to the dissociation of the complex Bi molecules. There are, however, a few exceptions to this general rule. Ag and I become more diamagnetic as the temperature rises (H). Crystalline Tin is slightly paramagnetic, liquid Tin is diamagnetic; but here we have grey Tin, which is still more diamagnetic.

5. Diamagnetic compounds, such as NaCl, HCl, H_2O, etc., do not show noticeable magnetic changes as the temperature or physical state is changed. This also would be expected from the magneton theory, because the simplest possible molecules of these substances contain no free magnetons, and are essentially diamagnetic: hence polymerization or solidification, which it should be observed is brought about in these cases by the electrostatic forces mentioned in §12 rather than by magnetic forces, cannot appreciably affect the magnetic susceptibility.

To summarize: As the changes,

$$\text{Complex molecule} \rightarrow \text{Simple molecule} \rightarrow \text{Atom},$$

take place, from whatever cause, we may expect, with the qualifications already noted, that diamagnetism will give way to paramagnetism. Gaseous dissociations are the cases where new evidence is most urgently needed—and where it is most difficult to get.

This collected evidence seems conclusive for para- and diamagnetic substances, but it is important to observe that we are driven to exactly the opposite conclusion in the case of ferromagnetism. Here it seems that it is easier to obtain a system with a large magnetic moment that is made up of constituents drawn from two or more atoms than to obtain such a system within a single atom. The conclusive evidence on this point is the behavior of the Heusler and similar alloys: in these, as has frequently been pointed out, the ferromagnetic units must be groups of several atoms; it is very likely, then, that the same is true for ferromagnetic elements like Iron. The way in which these complexes are built up is not at all indicated by the magneton theory up to the present; but see §19.

§23. Weiss' Magneton, and Quantitative Relations

With regard to a comparison of the results of the theory here described with Weiss' work on "the magneton," I will first quote a few sentences (translated) from the conclusion of a summary of his work that appeared in the Journal de Physique, [5] 1, 900, 965, 1911. These should be compared with the passages already quoted from Langevin (§2).

"What is the rôle of magnetic phenomena in chemical combination? Are chemical forces magnetic in nature? Are the valences, indeed, referable in some way to magnetons?" In the same paper he mentions the possibility that his magneton is the same as the unit magnet postulated by Ritz in the latter's theory of spectrum series.

Notwithstanding these suggestive passages, Weiss' magneton is not in any way identified with the electron, but is an empirical quan-

tity directly derived from the magnitudes of the susceptibilities of paramagnetic elements and compounds, and for such substances only: it has no meaning for diamagnetic substances. He maintains that the moments of paramagnetic atoms and molecules, when extrapolated to the absolute zero where the disturbing effect of molecular motions vanishes, are in simple integer ratio to one another. The highest common factor is 1122.7 for the paramagnetic salts, and 1123.5 for the ferromagnetic elements; and the agreement between these two values is certainly close. On this basis, the numbers of magnetons in some atoms and molecules are: Fe—11.0, Co—8.6, Ni—3.0 (8 and 9 at higher temperatures); $\frac{1}{3}(Fe_3O_4)$—4, 5, 6, 8, 10, in five successive states corresponding to five linear portions of the curve plotting the inverse of the saturation magnetism against the temperature. There follow his numbers (to the nearest integer) for some compounds:

In solution		*In the solid state*	
$K_3Fe(CN)_6$	10	$FeCl_3$	29
Ferric ammonium citrate	22	$FeCl_3 \cdot 2NH_4Cl \cdot H_2O$	27
$FeCl_3$	28	$FeF_3 \cdot 3H_2O$	21
$\frac{1}{2}Fe_2(SO_4)_3$	30	$FeF_3 \cdot 3NH_4F$	29
$NaFe^{II}$ oxalate	27	Fe^{III} acetylacetonate	25
$FeSO_4$	30	$\frac{1}{3}(Mn_3O_4)$	18
$KMnO_4$	4	$CrCl_3$	20
$CuSO_4$	10	Co^{II} acetylacetonate	21
$Cu(NH_3)_4SO_4$	6	——	
$U(SO_4)_2$	15	$\frac{1}{2}Neodym_2O_3$	18
$CoCl_2$	25	$\frac{1}{2}Sa_2O_3$	8
$MnSO_4$	30	$\frac{1}{2}Eu_2O_3$	18
——		$\frac{1}{2}Gad_2O_3$	41
		$\frac{1}{2}Ter_2O_3$	50
		$\frac{1}{2}Dyspr_2O_3$	56
		——	

With regard to the integral nature of the exact numbers, divergences of .1 or .2 are quite frequent, while there are values such as:

Co	8.6
Chrome alum (violet)	19.45
" " (green)	19.25
VCl_2	9.21
VCl_4	6.65
$\frac{1}{2}V_2O_3(SO_4)_2$	8.41

Thus the degree of approximation to integers seems to be about the same as in the case of the atomic weights of the elements. Further, in arriving at the number 9 (8.78) for the curious paramagnetic salt K_2HgI_4, Weiss makes corrections for the diamagnetism of the three constituent elements, a thing which is apparently not done in other cases.

It seems, therefore, that whatever may be the significance of the integral values for the metals Fe, Co, Ni (even here the value for Co is poor), the larger numbers obtained for the various hydrated and complex salts shown above cannot have any simple theoretical meaning—certainly none in so far as they may profess to represent definite numbers of natural unit magnets. Almost any mechanistic interpretation of Weiss' magneton involves the fallacy that elementary magnetic units can be additive in their effect on the magnetism of atoms and molecules in the same way as elementary electric units can be. This is no more true than that the moments of bar magnets, in an assemblage of such, are in general additive. Recently H. S. Allen (Phil. Mag., May, 1915) has discussed, in connection with Weiss' magneton, a magnetic atom model in which he surmounts this difficulty by ascribing the different magneton numbers to the presence of different numbers of electrons in a rotating ring, and to different angular velocities of this ring and of the central positive charge, which is also supposed to rotate. But the insuperable objections to hypotheses of rotating rings of electrons have already been explained (§2); and besides, the arbitrary nature of the assumptions which this model requires compares very unfavorably with the simplicity of Langevin's scheme or with the "automatic" way in which the model atoms of the present theory show a qualitative agreement with the most diverse facts of magnetism.

The futility of trying to express the magnetic properties of most atoms as simple functions of their magneton constitutions has been amply demonstrated in §§19-22. Apart from the paramagnetism expected in the isolated H atom, the only case in which, in the present state of the theory, we can make an absolute prediction of even the sign of the magnetism, is when the atom or molecule contains no free magnetons and only groups of eight. The atoms of He, Ne, A, Kr, Xe fulfill this condition, and for two of them we know the values (T):

$$\text{He } (\gamma)\ -38.8,$$
$$\text{A } (3\gamma) -212.8\ (=3\times 70.9) = (3\times 38.8) + 96.4).$$

Unlike paramagnetic moments, diamagnetic moments must always

be additive; but the value for Argon would be expected to be more than three times that for Helium, because groups of eight mutually strengthen one another (§11). Thus we may with some confidence take the susceptibility of the isolated group of eight to be about −38.8.

Now, while the groups of eight in the Argon atom are strengthened, those in "salt" molecules like K–Cl, H_2=O, H–Cl, etc. (which contain nothing but groups of eight), are weakened by the electrostatic strain set up by the transfer of magnetons from one atom to another: the groups of eight in such molecules retain their structure in spite of electrostatic forces.[1] We expect, then, what the following table shows to be the case—a decreased diamagnetism.

	–F	–Cl	–Br	–I	=O	≡N	–OH	–NO_3	=SO_4
H^{I}		—.80 —9.7			—.79 —7.1	—1.1 —9.3			
Li^{I}		—.47 —5.0							
Na^{I}	—.40 —4.1	—.41 —4.8	—.37 —5.4	—.31 —5.2				—.31 —2.9	—.64 —6.2
K^{I}	—.36 —4.2	—.47 —5.8	—.35 —5.2	—.31 —5.2				—.32 —3.2	—.42 —4.5
Ca^{II}	—.30 —3.3	—.39 —4.8			—.27 —3.0		—.39 —4.1		—.38 —4.0
Sr^{II}	—.26 —3.6	—.44 —6.3	—.31 —5.1	—.35 —6.3					
Ba^{II}	—.13 —2.1	—.32 —5.1	—.31 —5.4		—.10 —1.7		—.25 —3.9		
Zn^{II}		—.50 —6.8			—.26 —3.5		—.42 —5.2		—.53 —6.1
Cd^{II}		—.25 —3.8	—.30 —5.1	—.25 —4.6					
Hg^{II}		—.15 —2.5	—.24 —4.3	—.26 —5.1					

The numbers here are calculated from the data in the comprehensive work of Stephen Meyer on diamagnetism (*loc. cit.*). The upper

[1] Not merely one group of eight in the chloride ion, $\overset{-}{–Cl}$ (3γ) (which is got from the chlorine atom, Cl (2γ + 7)), suffers in this way, for the strain must be evenly distributed among all three.

value in each case gives the susceptibility per gram (small type) and the lower value the susceptibility per group of eight (large type). It may be seen that while the former varies between -1.1 and $-.10$ (ratio 11), the latter varies only between -9.7 and -1.7 (ratio 5.7): this makes the present view of the atom's structure seem all the more plausible.

We have seen on a broad scale the gradation between the reinforced, isolated, and strained groups of eight (susceptibilities -70.9, -38.8, and about -5, respectively); but it must be admitted that no gradations of a definite kind can be seen in the table just given for salt molecules. This may possibly be due to impurities in the materials used by Meyer. In any case a more careful scrutiny of these relations, with more accurate data perhaps, may yield some useful information about the structure of molecules.

NOTE ON EXPERIMENTS SUGGESTED BY THIS THEORY

1. The effect of a magnetic field on the electron concentration in an earthed conductor, or on the potential of an insulated conductor: A P. D. of 4×10^{-4} volt is expected for a field of 1,000 gauss, but there are many complications (§18).

2. The effect of a non-uniform magnetic field on the movements of the H atoms worked with by I. Langmuir: The expectations from this experiment are vague (§18).

3. The magnetic properties of monatomic Iodine gas, diatomic Sulphur gas, Sodium gas, N_2O_4 and NO_2, etc.: These determinations present forbidding difficulties.

Some of this work is under way, but it may readily be seen that the problems are of such a nature that the attainment of significant results may be a very slow and difficult process. This very circumstance, however, is a promising sign, for it is not likely that so important a property of the electron as is here dealt with would have remained undiscovered if the discovery of it were to be at all easy.

The absence of chemical problems from this list may be noted. Here, the theory has up to the present been occupied in correlating a vast body of facts and lesser generalizations in a field where the accumulation of experimental data has always far outstripped the assimilation of it into theory; and the result mentioned is therefore to be expected at this stage.

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THE JAW OF THE PILTDOWN MAN

(With Five Plates)

BY
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THE JAW OF THE PILTDOWN MAN

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(With Five Plates)

About three years ago Mr. Charles Dawson found the right half of an ape-like jaw in undisturbed material five feet below the level of the surrounding country in a gravel pit at Piltdown, Sussex, England. It lay in a depression at the bottom of the third and lowest stratum of the deposit, a band eighteen inches thick consisting of "dark brown ferruginous gravel, with subangular flints and tabular ironstone, pliocene rolled fossils .... 'eoliths,' and one worked flint" (Dawson and Woodward, 1914, p. 83). This third layer is supposed to be "in the main composed of pliocene drift, probably reconstructed in the pleistocene epoch" (Dawson and Woodward, 1914, p. 85). Within a yard of the same spot, and at precisely the same level, Dr. A. Smith Woodward later dug out a small piece of a human occipital bone. From this pit, and presumably from about the same part of it, other fragments were secured. They represent about half of a human braincase, a pair of human nasal bones, and a simian canine tooth; also teeth of beaver, horse, hippopotamus, rhinoceros, and two kinds of elephant. The human and simian remains were regarded by their discoverers as parts of one individual. On the basis of this assumption, though before the canine tooth and the nasal bones had been found, Dr. Woodward established a genus *Eoanthropus*, characterized by the combination in one skull of a human braincase and a completely ape-like jaw (Dawson and Woodward, April 25, 1913, p. 135).

Few recently discovered fossils have excited more interest than the "Dawn Man of Piltdown," and few have given rise to more discussion (see bibliography at end of this paper). Deliberate malice could hardly have been more successful than the hazards of deposition in so breaking the fossils as to give free scope to individual judgment in fitting the parts together. As a result no less than three restorations of the braincase already exist (see Gregory, 1914, fig. 9), while the canine tooth has been assigned to the right lower mandible and the left upper jaw. The estimates on the capacity of the braincase range from 1,070 to 1,500 cubic centimeters. While there is no doubt that

the braincase, whatever its exact size, represents a member of the family *Hominidæ,* there is wide difference of opinion as to the possibility of joining it with the mandible as parts of one skull. One author regards "this association of human brain and simian features" as precisely what he had anticipated (Smith, 1913, p. 131), while another says that it seems to him "as inconsequent to refer the mandible and the cranium to the same individual as it would be to articulate a chimpanzee foot with an essentially human leg and thigh" (Waterston, 1913, p. 319). I cannot find, however, that anyone has yet definitely identified the jaw as that of a member of an existing simian genus, or that any zoologist has attempted a detailed comparative study of this part of "*Eoanthropus.*" Dr. Woodward, who regarded the jaw as "almost precisely that of an ape," compared the specimens with young and adult chimpanzee only, while Dr. Gregory chose for his simian standard a female orang. Neither appears to have examined any considerable series of jaws of great apes.

Dr. Aleš Hrdlička has submitted to me a set of casts of the Piltdown fossils, and has suggested that I compare the mandible with the jaws of *Pongidæ* in the United States National Museum. This material includes the mandibles of 22 chimpanzees, 23 gorillas, and about 75 orangs. I have also had access to the series of human skulls in Dr. Hrdlička's custody. Study of these specimens, together with the general collection of primates in the museum, shows that the characters of the mandible and lower molars throughout the order *Anthropoidea* are much more diagnostic of groups than has hitherto been realized. It also convinces me that, on the basis of the evidence furnished by the Piltdown fossils and by the characters of all the men, apes, and monkeys now known, a single individual cannot be supposed to have carried this jaw and skull.

Analysis of the Published Opinions that the Jaw and Skull Were Parts of One Animal

The reasons that have been given for associating the jaw with the skull as parts of one animal are of three kinds: distributional, geological, and anatomical. They may be briefly reviewed before the characters of the fossil are taken up in detail.

The distributional evidence is negative. It is thus summarized by Dr. Gregory (1914, p. 194):

> The suggestion that while the braincase was human, the lower jaw belonged to another creature, an ape, is not in harmony with what is already known of the fauna and climate of Europe during pleistocene times. Thousands

of mammalian remains of pleistocene age have been discovered in the glacial and interglacial deposits of England and the Continent, but in this highly varied fauna the anthropoid apes have always been conspicuously absent, and there is no reliable evidence that any of the race ever lived in England during the pleistocene epoch.

In this statement two facts are not given their due weight; first, that the paleontological record is so fragmentary that unexpected discoveries need cause no surprise, and second, that a tooth from Taubach, Saxe-Weimar, described and figured by Nehring in 1895 as essentially similar to the first lower molar of a chimpanzee, had already indicated the possible occurrence of the genus *Pan* in Europe during the pleistocene age.

The geological evidence in favor of intimate association of the jaw and braincase is merely that the bones were found close together, at one level, and in a uniform condition of fossilization and water-wearing. These circumstances would give additional reasons for associating remains that presented no zoological difficulties; but when there is obvious incompatibility they do not furnish serious elements of proof. Mr. Dawson's remarks about the deposition of the other mammalian remains found in the same gravel apply with equal force to the skull and the jaw of *"Eoanthropus"*: the mere fact that they lay near each other means little. He says (Dawson and Woodward, 1913, p. 151):

> The occurrence of certain pliocene specimens in a considerably rolled condition, while the human remains bore little traces of rolling, suggested a difference as to age, but not to the extent of excluding the possibility of their being coeval. The rolled specimens might have entered the stream farther up the river than the human remains, and thus might have drifted into the hole, or pocket, in the river bed, where they were found, during the same age but in different condition . . . . It must be admitted that any attempt to fix any exact zoological date for specimens found in a gravel-bed is fraught with difficulties.

The anatomical reasons are (a) that the jaw "corresponds sufficiently well in size to be referred to the same specimen [as the braincase] without any hesitation" (Dawson and Woodward, 1913, p. 129); (b) that the measurements are "on the whole nearer to those obtained from early human jaws than to those of full-grown apes" (Gregory, 1914, p. 195); (c) that the molars recall human rather than simian teeth in their flattened, worn surfaces and their very thick enamel; and (d) that the condyle, or what remains of it, is more like the average human type than that of an ape. As to the relative size of the jaw and braincase nothing very definite can be said except that

no proof is afforded. To Dr. Woodward the parts appeared to present no discrepancies as to size; but to others who have examined the casts the jaw seems to be too lightly built to correspond with the massive cranial bones. A mandible as heavy as that of the pleistocene *Homo heidelbergensis* would probably be in due proportion; but the Piltdown jaw is even less robust than in well developed recent men. As regards actual dimensions the table on page 20 shows the wide divergence of the Piltdown jaw from both *Homo sapiens* and *H. heidelbergensis,* and its essential agreement with that of recent chimpanzees. Comparisons with *Gorilla* and *Pongo* are not necessary. About the teeth Dr. Woodward went so far as to say: "such a marked regular flattening has never been observed among apes, though it is occasionally met with in lower types of men" (Dawson and Woodward, 1913, p. 132). Yet I find that among nine chimpanzees with teeth at nearly the same stage of wear as in the type, the smooth condition shown by the fossil is closely approached by one individual and exactly matched by another (No. 84655, pl. 1, fig. 1, from cast, and pl. 2, fig. 1″, from actual specimen). While the thickness of the enamel is usually greater in *Homo* than in *Pan,* individual variation in both genera is sufficient to make this character, taken by itself, of little diagnostic value. The cast and Dr. Woodward's figures indicate that the Piltdown teeth have enamel differing in no essential feature from that of *Pan* No. 84655 (compare pl. 2, figs. 1″ and 2″). As regards the mandible of the fossil it must be remembered that the articular process is worn off to the level where it begins to widen and thicken to form the base of the condyle. From the characters of the part which remains Dr. Gregory reasoned that the condyles were "more slender, less expanded transversely, and supported by more slender pillars of bone" than in the great apes, features which would make the jaw "more like the average human type" (1914, p. 195). This conclusion may be true when the only alternatives considered are *Homo* and *Pongo,* but it does not hold good when the Piltdown jaw is compared with those of *Homo* and *Pan.* The articular process near level of fracture shows more lateral compression than I have been able to find in any specimen of *Homo,* and there is no indication of the deep concavity beneath the inner two-thirds of anterior edge of condyle which is a conspicuous feature of this region in *Homo* as compared with all the great apes. While the outer border of the fracture is unusually long relatively to the posterior and inner borders of the same region as seen in most specimens of *Pan,* the conditions in the Piltdown jaw would be almost exactly

reproduced by similar mutilation of the articular process of No. 174699, an adult female chimpanzee from French Congo. The arguments from anatomy, like those from geology and geography, are thus seen to have little force.

Mandibular Characters of the Anthropoidea

Before trying to decide how much importance should be assigned to the peculiarities of the Piltdown jaw it is necessary to understand the more conspicuous mandibular characters of the *Anthropoidea*.

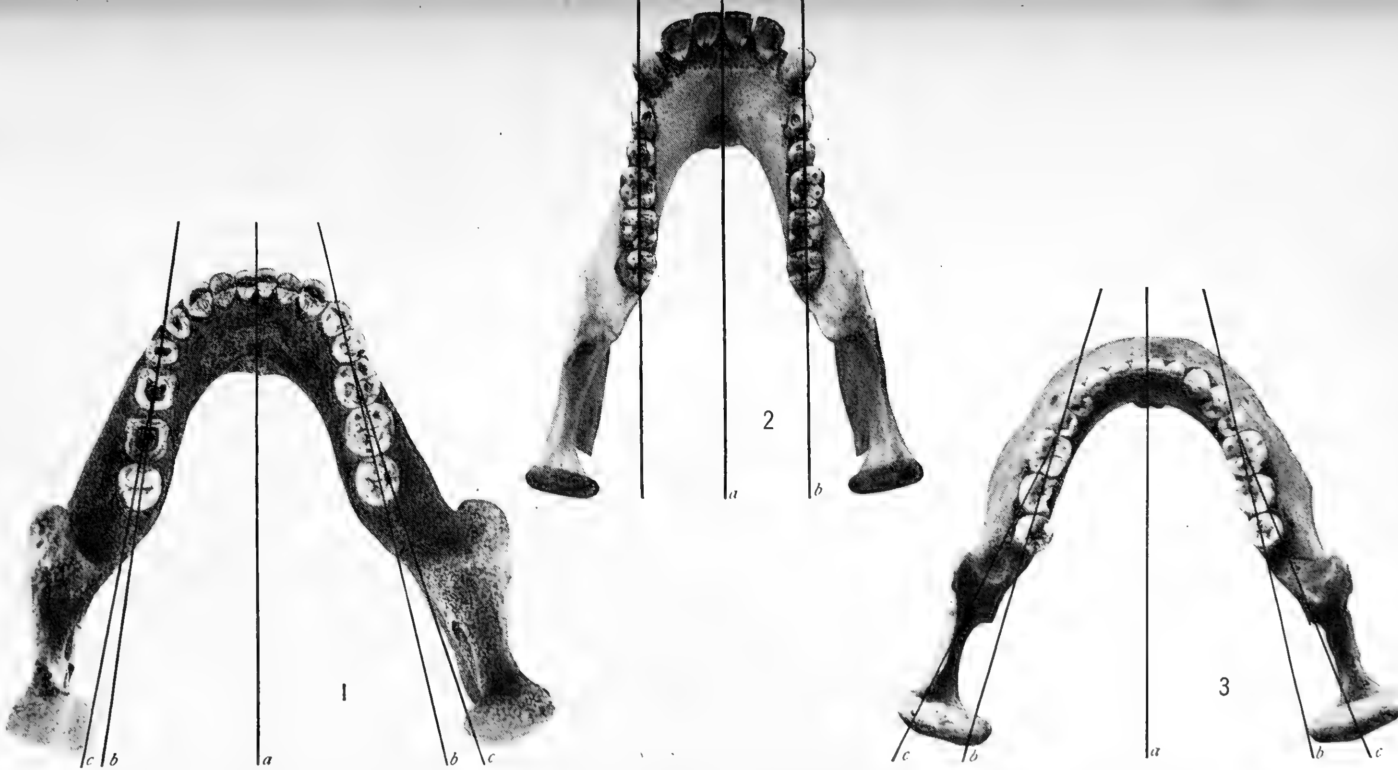
In the *Hominidæ*[1] as in all other *Anthropoidea* the mandibular halves become completely ossified at the symphysis soon after birth. This character distinguishes members of the order from the recent *Lemuroidea,* in all of which the halves remain distinct. Two main peculiarities of the lower jaw and its toothrow separate the *Hominidæ* from other *Anthropoidea* and especially from the great apes. The two halves of the jaw together form a horseshoe-like arch (text fig., 1 and 3, and pl. 3), so broadly rounded in front that the width between the anterior molars is decidedly greater than the distance from the first molar to the symphysion, and so widely open behind that the distance between the condyles (outer borders) is conspicuously greater than that from condylion to symphysion. In other members of the order the arch is so narrow that the distance between the anterior molars never exceeds that from first molar to the symphysion, and the distance between the condyles rarely if ever equals that from condylion to symphysion (text fig., 2, and pl. 4). The toothrow in the *Hominidæ* is narrowed and weakened in front of the molars, the change taking place abruptly with posterior premolar. Each premolar is single rooted, and the crown-area is less than half that of the first molar. The canine never projects conspicuously above the general level of the other tooth summits; its size, form and function are essentially incisor-like. Among the great apes the robust character of the toothrow is carried forward through the large, double-rooted premolars to the strongly functional canine, the point of which rises in males conspicuously above the general level of the other teeth. Together with its anterior weakening the toothrow as a whole is characterized in the *Hominidæ* by a widely arched form corresponding to that of the jaw. The inward curve on each

[1] Including the various living species of *Homo* and the pleistocene *H. neanderthalensis* King and *H. heidelbergensis* Schoetensack, but excluding, as members of the family *Pongidæ,* the genera *Pithecanthropus* Dubois and *Sivapithecus* Pilgrim.

side begins with the molars, while in the great apes it begins with the premolars or canines. A line joining the middle of posterior border of m_2 with the middle of anterior border of m_1, will, if continued forward in front of incisors, converge rapidly with the sagittal line similarly extended (text fig., 1 and 3, b). In the great apes and in most of the monkeys except certain smaller South American forms a line passing through middle of posterior border of m_2 and middle of anterior border of m_1 is essentially parallel to the sagittal line (text fig., 2, b). In the *Hominidæ* the inward curve of the tooth-row normally begins with the first lower molar. The axis of this tooth prolonged backward (text fig., 1 and 3, c) diverges rapidly from a line parallel to the sagittal plane and crosses the posterior border of m_2 on outer side of middle; continued still further it passes through the condyle. That of the second tooth similarly prolonged, while diverging slightly from a line parallel to the sagittal plane, passes considerably to inner side of condyle. In all living genera of great apes and in the fossil *Propliopithecus, Dryopithecus,* and *Sivapithecus* the axes of the two teeth (text fig., 2, b) lie in one line essentially parallel to the sagittal line and passing further to inner side of condyle than is the case with the axis of m_2 in the *Hominidæ*. The symphysial region in the *Hominidæ* seldom extends conspicuously behind the level of the incisors, and never bears a marked concavity on its posterior border for insertion of the lingual muscles; in other primates it always extends conspicuously behind level of incisors and it usually bears a marked concavity on its posterior border. The mylohyal ridge is well developed in the *Hominidæ,* but is barely indicated in monkeys and apes.

While sharing those general peculiarities which distinguish other primates from the *Hominidæ,* the three[1] genera of living great apes are readily separable from each other by the details of their mandibular structure. In *Pan* and *Pongo* the digastric muscle is inserted along the lower border of the mandible, rarely extending forward

[1] In the most recent complete work on the order, Elliot's "Review of the Primates," New York (1912), June, 1913, four genera are recognized: *Pongo* Lacépède for the orangs, *Gorilla* I. Geoffroy for the gorillas, *Pseudogorilla* Elliot (l. c. vol. 3, p. 224) for an animal supposed to be the *Gorilla mayema* of Alix and Bouvier, and *Pan* Oken for the chimpanzees. The genus "*Pseudogorilla*" was based on two specimens of true *Gorilla,* an immature male with all the teeth in place but with the basal suture open and the temporal ridges separate (l. c. pl. 32), and a mature female with the basal suture closed and the temporal ridges joined (l. c. pl. 33). Three valid genera are thus left in the group.



TEXT FIG.—Lower jaws (about half natural size) of: 1, *Homo heidelbergensis* (after Schoetensack): 2, *Pan* sp. (No. 176226, southern Kameroon); and 3, *Homo* sp. (No. 278783, Urga, Mongolia). *a* sagittal line, *b* line joining middle of anterior border of m_1 with middle of posterior border of m_2, *c* axis of m_1. In No. 2, *c* is not different from *b*. The specimen figured as No. 3 was selected to show wide divergence of *b* and *c* from *a*; in many recent individuals the conditions are essentially as in No. 1. Anomalies are not infrequent.

beyond the extreme posterior edge of the bone. This region of attachment forms a thin, sharply-defined ledge beneath the pit in which the other tongue-muscles are inserted. While the lower border is essentially alike in the two genera the pit is deeper and narrower in *Pan* than in *Pongo* and its upper border is usually well-defined by an abrupt convexity in the posterior profile of the symphysis; the hinder margin of this convexity lying at level of canine or anterior premolar. In both genera the region of temporal muscle-insertion is characterized by the presence of a distinct and narrow ridge curving upward from behind the alveoli and extending to or above the middle of the coronoid process. While they thus agree in certain characters the two genera differ from each other in the form of the symphysis, which, like the entire horizontal ramus, is deeper in *Pongo* than in *Pan*. The base of the articular process in *Pan* is strengthened by a conspicuous ridge extending obliquely downward on the inner side of the mandible. In *Pongo* this ridge is barely indicated. Below the ridge in *Pan* a distinct groove extends upward and backward from the dental foramen; this is scarcely visible in *Pongo*. Turning to *Gorilla* it is seen that the digastric muscle pushes conspicuously forward under posterior border of mandible, so that the ledge beneath the pit is broadly rounded off. The pit is small and ill-defined, and the region which it occupies is carried so far backward by the very gradually sloping symphysis that its upper margin lies at level of posterior premolar. In the region of temporal muscle-insertion the ridge extending upward toward the coronoid process is usually deflected forward below the base of the process. The dental foramen and the region behind it are about as in *Pongo*. The strengthening ridge of articular process is more evident than in *Pongo* but less defined than in *Pan*.

The lower molars in the living primates represent three main types of structure, peculiar respectively to: (a) the American monkeys, (b) the *Hylobatidæ*, great apes,[1] and *Hominidæ*, and (c) the remaining Old World forms. The first type (most clearly shown by *Alouatta*) is essentially that of the more primitive lemur molars (as in *Propithecus*) modified by partial or complete suppression of the paraconid and by various degrees of flattening out of the original triangles, with no addition of new elements. In the second type the paraconid is absent (sometimes a faint trace in *Gorilla*) and there is normally a well-developed talonid. The posterior half of the crown is, as in the first type, basin-shaped; and any transverse ridge which

[1] Also in the extinct genera *Dryopithecus* and *Sivapithecus*.

it may bear extends obliquely between hypoconid and talonid. In the third and most specialized type the paraconid is absent, the talonid is not well developed except in m_3, and the posterior half of the crown is not basin-shaped. The region occupied by the hollow in the other types is here filled by the bases of the hypoconid and entoconid. Usually the bases of these cusps join to form a high, squarely-transverse ridge.

While the great apes and the *Hominidæ* agree in the fundamental structure of their lower molars each genus shows obvious characters of its own. In *Gorilla* the crowns are low and the cusps high, subterete and more conspicuous than in any of the others. The cingulum on anterior border of m_1 sometimes bears a nodule which may be the last remnant of the paraconid, a character which I have found in this genus only. The talonid of m_3 is very distinct, often larger than the hypoconid and often connected with the hypoconid by a rudimentary oblique transverse ridge. The cingulum at the postero-internal border of crown occasionally bears a minute cusp, while sometimes it is completely transformed into a well-developed single or double cusp. The secondary folding of the enamel is evident, but not sufficiently developed to obscure the plan of cusp-arrangement. A low supplemental cusp is sometimes present between the protoconid and the hypoconid. In *Pan* the depressions between the cusps are not so deep as in *Gorilla,* so that the crowns appear to be less brachydont and the cusps less terete and less conspicuous. The talonid in m_3 is less developed than in m_1 or m_2, not larger than the hypoconid. Cingulum of postero-internal border often so thickened as to form a supplemental cusp. The secondary folding of the enamel is more evident than in *Gorilla;* it tends to obscure some of the details of the cusp-arrangement. In *Pongo* the cusps take the form of ridge-like elevations at the extreme border of the shallow depression which occupies most of the surface of the crown. The talonid is well developed but is somewhat obscured by the flattening common to all the cusps and by the extremely conspicuous and complicated secondary enamel folding which covers almost the entire surface of the teeth except the summits of the main cusps. In the *Hominidæ* the crowns are slightly less brachydont than in any of the genera of great apes; and the cusps are less distinctly outlined by intervening depressions. Viewed from above they are seen to be less squarely truncate, so that each tooth comes less broadly in contact with the one in front of it (compare pls. 3 and 4). This rounding off at the sides takes place in front at expense of both protoconid and metaconid. There is a similar reduction at the posterior border,

making the entire tooth shorter and more nearly circular in outline than in any of the great apes. The posterior shortening occurs in the region occupied by the talonid and the postero-internal cingulum. The talonid is therefore less constantly present than in the great apes, though it appears to occur normally in m_1 (where it is sometimes divided into two cusps), often in m_3, and less frequently in m_2; rarely it is present in all three teeth. The postero-internal cingulum is seldom a noticeable element. The secondary enamel folding though present is less evident than in any of the great apes. In general the lower molars of the *Hominidæ* may be described as like those of *Pan* but with higher crowns, lower, broader, less sharply-marked-off cusps, less wrinkled enamel, and more rounded-off anterior and posterior borders, the rounding-off behind practically eliminating the postero-internal cingulum and decidedly reducing the talonid or "fifth cusp" (compare pls. 3 and 4).

Two main facts are now evident: that among the living and recently extinct great apes and *Hominidæ* (a) all the more important features of each group remain constant in such widely separated forms as *Homo sapiens* and *H. heidelbergensis*[1] on the one hand and *Pongo, Gorilla* and *Pan* on the other, and (b) each known genus is sharply differentiated from all the others by characters visible in the Piltdown jaw.

Comparison of the Piltdown Jaw and Teeth With Those of Other Members of the Order

The Piltdown jaw (pl. 1, fig. 2, and pl. 2, fig. 2) admittedly differs from every known mandible of living or extinct members of the family *Hominidæ*. Although broken away a little to the right of the symphysis, it has an abrupt anterior bend which is exactly that of a great ape. The symphyseal region extends conspicuously behind the level of the incisors. The region of the mylohyal ridge is smoothly rounded. The two molars (pl. 2, fig. 2) show no indication of the beginning of a curve in the toothrow. The main axis of the first tooth is continued backward by that of the second in a line passing as far to inner side of condyle as in the *Pongidæ*. In front of the first molar the entire hinder border of the alveolus of pm_4 is plainly visible. It shows that the missing tooth was fully as large as in the great apes

[1] Regarded as a distinct genus by at least two authors: Bonarelli, Revista Ital. di Paleont., Perugia, vol. 15, p. 26, March 15, 1909 (*Palæanthropus*); and Ameghino, An. Mus. Nac. de Buénos Aires, vol. 19 (ser. 3, vol. 12), p. 195, July 27, 1909 (*Pseudhomo*).

and that the toothrow did not become abruptly weakened at the point where this conspicuous change takes place in all known *Hominidæ*. The molars are distinctly less hypsodont [1] than in recent or pleistocene *Hominidæ*. On the outer surface of each tooth there is a trace of a deep sulcus extending downward between the protoconid and the hypoconid nearly to the lower border of the enamel in a manner rarely seen in *Homo* (compare pl. 3 with pl. 2, figs. 2″ and 4) but constant in *Gorilla, Pan* and *Pongo*. In each tooth there is a large talonid and a postero-internal cingulum, better seen in the photograph (pl. 2, fig. 2″) than in the cast (pl. 2, fig. 2′). The anterior border of the crown is squarely truncate; and the general outline of each tooth is unlike that known in any recent or fossil man.

Though its general characters are the same as those of all the living great apes, the Piltdown jaw is readily distinguishable from jaws of *Pongo* and *Gorilla*. There is no trace of the deepening of the horizontal portion of the mandible characteristic of *Pongo*, nor do the teeth show any indication of ridge-like cusps and heavily wrinkled enamel. Enough of the symphyseal region remains to prove that this did not extend backward as in *Gorilla;* while the teeth differ at least as widely from those of *Gorilla* as from those of *Pongo*. Comparison with the mandible of *Pan* brings out no such discrepancies. On the contrary there is agreement in all the features which distinguish *Pan* from the two other genera: in depth of horizontal portion, in form of symphysis, in the ridges on inner side of ascending ramus, and in the peculiarities of dental foramen and the groove behind it. On plates 1 and 2 the Piltdown jaw is compared with casts of the mandibles of two African chimpanzees mutilated in as nearly as possible the same manner. It will be seen that the main peculiarities of the fossil, apart from the large teeth and robust horizontal shaft, lie within the limits of variation shown by these two African specimens. In another African specimen (No. 174710, pl. 5, fig. 2) the depth of shaft as well as that of the ascending branch is essentially equal to that in the fossil (see table of measurements, p. 20). Further details of variation in the mandible of recent chimpanzees are shown in plate 5. The teeth resemble those of certain living chimpanzees in structure, agreeing in all essential features with those of Pan No. 176226 from southern Kameroon (compare pl. 2, figs. 2″ and 4; allowances must be made for the different degree of wear in the two sets of teeth, and for

[1] In the cast and in the photograph (Woodward, 1915, pl. 4); in the original figure (Dawson and Woodward, 1913, pl. 20) the crowns are represented as essentially human in height.

the fact that the enamel is absent from the antero-internal corner of m_1 in the recent specimen). Their size is greater in proportion to that of the jaw than in any recent material that I have seen. From modern African specimens of *Pan* the Piltdown jaw differs therefore in mere details of proportion and in the actual size of the molar teeth.

The canine tooth found in the Piltdown gravel did not form part of the remains on which the genus "*Eoanthropus*" was based. Yet its interest is so great that it deserves special attention. Of this tooth Dr. Woodward says: it "obviously belongs to the right side of the mandible . . . . and its worn face shows that it worked with the upper canine in true ape fashion" (1913: Nature, p. 110, Geol. Mag., p. 432), while Dr. Gregory remarks: "Its resemblances are on the whole closer to the left upper canine." Boule (1915), however, leaves the tooth in the lower jaw without comment. As "the enamel on the inner face of the crown has been completely removed by mastication" (Dawson and Woodward, 1914, p. 87) and the worn area is a wide, shallow concavity directly backward and inward, there is no reason to doubt the correctness of the second view. Such mechanical interrelation of the teeth as would produce a worn surface of this kind on a lower canine is not only unknown among primates, but I have been unable to find any mammal with the upper and lower teeth so arranged that it could exist. A concavity on the inner aspect of the lower canine may be present, as in adult *Propithecus* or in the milk tooth of *Homo,* but not as the result of gouging out by an upper tooth. The fact that its concave surface is worn therefore removes all significance (Dawson and Woodward, 1914, p. 91; Woodward, 1915, p. 23) from the superficial resemblance of the Piltdown tooth to the lower milk canine of man. In all the living great apes the postero-internal surface of the lower canine is convex (see pl. 4, and Woodward, 1915, fig. 8A as compared with fig. 8B). The worn area normally appears first at the summit of the tooth, then extends down the postero-internal limb of the convexity; later it may spread to the antero-internal surface, and in aged individuals may reduce the tooth to a flattened stub. No matter how long a lower canine may have been in use it never assumes the form seen in that of "*Eoanthropus,*" nor does it lose all trace of the original convexity of its inner portion. The upper canines, on the other hand, are normally worn away over exactly the same area as in the Piltdown tooth. Among the living great apes, while there is much individual variation in size and form, the canines are larger and higher-crowned in males

than in females. Comparison of the Piltdown tooth with those of males of all three genera and of females of *Gorilla* and *Pongo* show numerous and striking discrepancies which need not be detailed here. On comparison with the left upper canine of adult female *Pan*, however, no such discrepancies are found. The cast of the tooth almost fits the left alveolus of No. 174700, an adult female chimpanzee from French Congo. Its greater size and straighter, more compressed root prevent its taking a wholly natural position in the socket; but when as nearly as possible in place it is in all important respects symmetrical with the canine of the right side and with the cheek-teeth of the left series. The only characters by which I am able to distinguish it from the corresponding tooth of adult female recent chimpanzees are the slightly greater size, the less backward-bent extremity of root, and the greater area and deeper concavity of the worn region on postero-internal aspect of crown. The distinction of root from crown is not so well marked as in recent teeth, but this circumstance is probably due to the incomplete condition of the enamel which Dr. Woodward (Dawson and Woodward, 1914, p. 87) has described.

Incompatibility of the Piltdown Jaw and Skull

Discussion of the relationships of the man represented by the Piltdown braincase to the various living and extinct species of *Homo* does not come within the scope of this paper. Certain characters of the skull-fragments are, however, of special importance in connection with the supposed association of the jaw with those remains.

The occipital bone has been said to approach "a lower [than typically human] grade . . . . in the attachment for the neck" (Dawson and Woodward, 1913, p. 132). On comparing it with a few dozen recent human skulls taken at random from the series in the National Museum I find that its peculiarities of form are so exactly matched that none can be regarded as of more than individual importance. The "relatively large extent and flatness of its smooth upper squamous portion" (l. c. p. 128) is completely within the range of variation in modern species of *Homo*. This feature, connected as it is with the upright position of the body, and the consequent shrinking of the area for attachment of the neck-muscles, is one of the family characters of the *Hominidæ*. In the *Pongidæ* a very small smooth area[1] is present in the young above the region of muscle-attachment, but in the adult this area is always encroached on[2] and often obliterated

[1] More noticeable in *Gorilla* and *Pan* than in *Pongo*.

[2] More rapidly and completely in *Gorilla* and *Pongo* than in *Pan*.

by the constantly increasing lambdoid crest. The fact that the squamous portion of the occipital bone is well developed in the fossil therefore indicates wide divergence from the known great apes. Another fancied resemblance to the *Pongidæ* is seen by Boule, who remarks (1915, p. 59) that to him the lower curved line appears to lie relatively nearer to the upper curved line than in recent *Homo,* its position thus more as in *H. neanderthalensis* and still more as in the chimpanzees. The distance between the two lines in the Piltdown skull is 15.5 mm. In two adult skulls of American Indians, one from Illinois (No. 243881) the other from North Dakota (No. 228876), which happened to be lying side by side in one of the exhibition cases it is respectively 14.5 mm. and 27 mm. Among adult chimpanzees I find extremes of 15.5 mm. (No. 174790) and 24.5 mm. (Nos. 84655 and 176227). When a character varies so much in both genera no conclusion can be based on the conditions found in any one skull. Even if a conclusion regarding the lines were justified it would have little meaning in view of the strictly human features of all other parts of the occipital bone.

Aside from the superior maxilla the parts of the skull most directly related to the mandible are: (a) the point of actual contact, (b) the region of origin of the masseter muscle, and (c) that of origin of the temporal muscle. Of these three the first and last are well preserved in the fossils. The glenoid region has been recognized as "typically human in every detail" (Dawson and Woodward, 1913, p. 128). Comparison with many human skulls shows that it presents the characteristically human features of narrow articulating surface and deep fossa in a much more than usual degree of development. Unfortunately the absence of the condyle makes it impossible to know whether the corresponding surface of the Piltdown jaw had the broad and slightly convex form seen in all three genera of living *Pongidæ;* but the part immediately below the fracture shows, in the region over the dental foramen, the highly developed strengthening ridge characteristic of the genus *Pan* (see pl. 1). A slight indication of the ridge is often present in *Homo;* but I have been unable to find a specimen even among those in a set particularly selected to illustrate the variations of human mandibles, in which the structure of this region agrees with living chimpanzees and the Piltdown jaw. The facts are that the Piltdown skull presents extreme human characteristics in the glenoid region calling for correspondingly extreme human conditions of narrow and strongly convex articular surface in the mandible which hinged on it. But this entire mandible, from sym-

physis to base of condyle, is like that of a chimpanzee. Hence in order to fit its articulating surface to that of the skull it would be necessary to imagine an abrupt change of plan in the few millimeters of condyle that have been lost.

Another incongruity is found when the area of origin of the temporal muscle on the skull is compared with that of its insertion on the mandible. Both regions have been carefully described and figured (Dawson and Woodward, 1913, pp. 128, 131, pl. 18, fig. 3, pl. 20, figs. 2a, 2c). The anterior border of the muscle appears to have extended upward on the frontal with somewhat unusual abruptness, an impression that may be heightened by the way in which the bone is broken. The posterior border was not carried very far back on the parietal. In general features the area of origin for the whole muscle is strictly human, and its extent is considerably less than in many of the human skulls with which I have compared it. In all three genera of *Pongidæ* this area is much greater in proportion to the size of the animal, pushing its way in adult individuals gradually over the braincase to median line, where the muscles of the two sides are often separated merely by a sagittal crest.[1] The area of insertion of the muscle on the Piltdown mandible has not only all the more important general characters peculiar to this region in *Pan;* it has also the individual features which in living members of that genus are connected with the greatest extension of the area of origin of the muscle on the skull. Young chimpanzees show a slight approximation to *Homo* in the form of the area on which the temporal muscle is inserted. The ridge which extends upward from the base of the coronoid process is broad and low, giving this whole region the smoothly convex appearance usually found in members of the family *Hominidæ.* With increasing age the ridge becomes narrower and the region behind it changes from flat to concave; finally the surface of the main ridge becomes marked by secondary ridgelets which give extreme strength of attachment to the muscle-fibers. This last stage of roughening on the mandible is associated in chimpanzees with the closest approach of the upper end of the muscle to the median line of the braincase and especially with the formation of a sagittal crest. It is well-marked in the Piltdown jaw. In order to associate this jaw with the braincase it would therefore be necessary to assume the existence of an animal related to both *Homo* and *Pan* but with a temporal muscle working on a different mechanical scheme from either; that is, moderate in size and strength at the

[1] Most frequently developed in *Gorilla,* least frequently in *Pan.*

region of origin on the skull and excessively heavy at the mandibular end. That such an animal may have lived cannot be denied; but nothing so contrary to the facts which are now known need be believed without the evidence of a jaw found in place.

Two other features of the human skull, both connected with the upright position of the body, and both represented by the Piltdown fragments, have an important bearing on the question of the association of the mandible with the braincase. One of these is the form of the basicranial region, the other is that of the nasals. That human skulls differ from those of other primates in the position of the foramen magnum and the occipital condyles appears to have been first clearly recognized by Daubenton, as long ago as 1764.[1] The subject has received attention from many subsequent authors.[2] While some individual variation in this respect is shown by recent man, and the conditions may prove to be less pronounced in the Pleistocene *Homo neanderthalensis* than in living members of the group,[3] the family *Hominidæ* is distinguished from all other mammals by the fact that the occipital region is so produced behind the condyles, while at the same time the anterior maxillary region (including front of lower jaw) is so retracted, that the points of support on the erect upper portion of the vertebral column stand essentially beneath the center of gravity of the skull, thus balancing the head in its characteristic poise. As a result of the maxillary retraction the nasal floor is shortened anteriorly and the nasal aperture is made to open directly forward instead of forward and upward. The nasal bones roofing this modified aperture are normally thrown into a prominence unknown in any monkey or great ape. Whether the maxillary retraction came about primarily as part of a general readjustment of the skull to its upright attitude or through other agencies, the fact remains that this character is not yet known among primates except as part of a set of changes, one result of which is to bring the point of cranial support to the position where it affords the most effective balance. In all primates other than the *Hominidæ* the condyles lie behind the center of gravity and the head is held in place on the oblique or horizontal anterior portion of the

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[1] Mém. Acad. Roy. Sci., Paris (1764), pp. 568-577. 1767.

[2] See, for instance, Huxley, Man's Place in Nature, p. 76, 1863; Owen Comp. Anat. and Physiol. Vert., vol. 2, p. 554, 1866; Broca, Rev. d'Anthrop., Paris, vol. 2, pp. 193-234, 1873 (reprint in Mém. d'Anthrop., vol. 4, pp. 595-641, 1883); Papillault, Bull. Soc. Anthrop., Paris, ser. 4, vol. 9, pp. 336-385.

[3] See Boule, Ann. de Paléont., vol. 6, pp. 156-159, 1911 (l'Homme fossile de la Chapelle-aux-Saints, pp. 48-51).

vertebral column by strong muscles;[1] the anterior maxillary region is not retracted, and the nasal bones are flatly sunk into the interorbital region and the upper border of the nasal orifice. In the *Hominidæ* the peculiar position of the condyles is accompanied by special modifications in the floor of the braincase. The area between the foramen magnum and the choanæ is bowed upward, the mastoid process is carried downward and forward until it almost encroaches on the region lying below glenoid notch, and the tympanic plate and entire petro-mastoid are distorted from their primitive form. The temporal bone of "*Eoanthropus*" (Dawson and Woodward, 1913, pl. 19, fig. 2) shows by its exact resemblance to the same bone in *Homo* that this fundamental part of the skull was completely adjusted to the task of supporting a human brain in the upright position. Belief that a primate like the one to which this temporal bone belonged, and living as recently as the late pliocene or early pleistocene, lacked that corresponding balance-adjustment in the maxillary region which is present in all members of the *Hominidæ* actually known, cannot reasonably exist without the evidence of an entire specimen; yet such absence of mechanical unity between the two parts of the skull must be assumed in order to provide the specimen with a long, narrow upper arch to fit the lower jaw[2] (compare pls. 3 and 4). Similarly, in the absence of a specimen showing human nasal bones coexisting with the protruding anterior maxillary region of the great apes, there is every reason to suppose that the Piltdown jaw was not closely associated with this pair of typical human nasals (Dawson and Woodward, 1914, pl. 15, fig. 1) until the deposition of the remains near each other in the old river-bottom. It is not improbable that ancient

[1] A peculiar instance of approach to a balanced condition of the head is furnished by the South American monkeys of the genus *Saimiri*. Here the back part of braincase protrudes so far that the condyles are made to be nearer the middle of the skull than in any other monkey that I have examined. There is no indication of a general readjustment of the skull, the base of braincase together with the facial region remaining as in related genera.

[2] As the cranial floor between the temporal bone and the median line is not represented by the fragments it is perhaps not safe to assume that the distance from one glenoid to the other was as great as in recent *Homo*. Every feature of the specimen makes it appear probable, however, that such was actually the case. If this human widening existed, the articular surfaces of the corresponding jaw, to accord with the conditions present in all other known primates, should have been wide apart, the jaw should have been strongly arched, and the lower toothrow should have begun to bend inward behind the premolars. Neither the teeth nor the horizontal portion of the Piltdown mandible present any such characters.

fossil forms will be found in which the characters of face, braincase, jaws and teeth are so generalized as to represent a structure that could have given rise to the distinguishing features of both *Hominidæ* and *Pongidæ*. But nothing could be more contrary to the conditions present in all living and fossil *Anthropoidea* now known than the simultaneous occurrence in a pleistocene or recent genus of fully developed fundamental characters elsewhere diagnostic of the two groups.

Summary

The Piltdown remains include parts of a braincase showing fundamental characters not hitherto known except in members of the genus *Homo,* and a mandible, two lower molars, and an upper canine showing equally diagnostic features hitherto unknown except in members of the genus *Pan.* On the evidence furnished by these characters the fossils must be supposed to represent: either a single individual belonging to an otherwise unknown extinct genus (*Eoanthropus*), or two individuals belonging to two now-existing families (*Hominidæ* and *Pongidæ*). The fossils are so fragmentary that their zoological meaning will probably remain a subject of controversy. Yet the weight of the difficulties on the two sides is unequal. In order to believe that all the fragments came from a single individual it is necessary to assume the existence of a primate differing from all other known members of the order by combining a braincase and nasal bones possessing the exact characters of a genus belonging to one family, with a mandible, two lower molars, and an upper canine possessing the exact characters of a genus belonging to another. Thus must be associated in a single skull: (a) one type of jaw with another type of glenoid region, (b) one type of temporal muscle-origin with another type of temporal muscle-insertion, (c) a high degree of basicranial adjustment to the upright position with absence of that corresponding modification in the lower jaw called for by all that is now actually known of the structure of the braincase and mandible in primates, and (d) a protruding lower jaw with a form of nasal bone not elsewhere known except in connection with a retracted upper dental arch. In each instance the opposed characters are sharply defined and easily recognizable in the fossils; while in no single feature is there any trace of the blending of the two types. On the other hand the assumption that the skull and jaw belonged respectively to a man and a chimpanzee carries with it only two difficulties: (a) that of the deposition within a few feet of each other of the remains of two animals whose bones are rarely found in gravel

pits, and (b) that of the supposed absence of chimpanzees from the European pleistocene faunas. Concerning the first nothing can be said, except that those local conditions which caused the deposition of one specimen near a given spot might be expected to act in about the same way with another. The second is at least partly met by the fact that a tooth described and figured as not certainly distinguishable from the first lower molar of a chimpanzee has been found in the pleistocene of Germany. Until the discovery of further material it seems proper to treat the case as a purely zoological problem by referring each set of fragments to the genus which its characters demand.

The British Pleistocene Chimpanzee

Accepting the conclusions (a) that each set of the Piltdown fragments shall be treated according to the existing characters, and (b) that the characters of the lower jaw are those of a member of the genus *Pan,* it becomes necessary to distinguish the British pleistocene chimpanzee from the living African species. No special fragment was designated by Dr. Woodward as the type specimen of *Eoanthropus dawsoni.* As the species was referred to the family *Hominidæ* I now restrict the name to the human elements of the composite, selecting as type the temporal bone (Quart. Journ. Geol. Soc. London, vol. 69, pl. 19, fig. 2). For the chimpanzee represented by the mandible with its first and second molar teeth I propose the name:

PAN VETUS, sp. nov.

(Pl. 1, fig. 2, pl. 2, fig. 2)

Diagnosis.—General characters of mandible and of first and second lower molars as in living species of *Pan* from French Congo and southern Kameroon, but horizontal ramus more robust and teeth larger.

Measurements.—In the table (page 20) the measurements of the type (from cast) are compared with those of seven mandibles of *Pan* from French Congo and Kameroon, among which are represented the maximum and minimum dimensions for the entire National Museum series of adults. Only one of these individuals contrasts noticeably with the type in the worn condition of the molar crowns. For convenience of further comparisons I have added the measurements of *Homo heidelbergensis* (from cast) and of three specimens of modern *Homo,* one extremely large, another medium in size and the third rather small.

TABLE OF MEASUREMENTS.

Locality.	Number.	Sex.	Length of mandible at alveolar level from posterior border to symphysion.	Distance from posterior border of mandible to front of m_1 (alveolus).	Diameter of ascending ramus at alveolar level.	Depth of ascending ramus from lowest point of sigmoid notch.	Depth of horizontal portion at middle of m_3.	Depth of horizontal portion at middle of m_1.	Width of horizontal portion at middle of m_3.	Greatest width of horizontal portion below middle of m_1.	Combined alveolar length of three molars.	Crown of first molar.	Crown of second molar.	Worn condition of teeth as compared with those of *Pan vetus*.
***Pan* sp. (recent).**														
French Congo	174707	♀	109.4	68.0	40.6	....	21.2	23.0	14.8	10.6	31.4	10.2×9.6	11.0×9.8	Slightly less.
French Congo	174701	♀	113.6	72.0	44.0	49.0	29.4	27.6	16.6	12.9	32.0	10.8×10.0	11.2×9.8	Distinctly less.
S. Kameroon	176229	♀	117.4	77.8	51.2	49.6	27.6	30.2	17.0	13.8	32.0	10.0×9.0	11.0×10.0	Slightly more.
French Congo	174699	♀	120.4	78.4	47.6	47.4	27.2	27.7	16.8	15.2	34.6	....	....	About the same.
French Congo	174710	♀	123.3	80.4	50.6	62.0	28.0	30.6	16.4	13.0	32.6	10.0×9.6	10.8×10.0	Noticeably more.
S. Kameroon	176235	♂	115.7	80.0	51.6	52.4	24.2	26.4	17.2	14.6	33.8	10.6×10.6	11.0×11.6	Slightly less.
French Congo	174704	♂	125.8	81.0	52.0	61.2	27.2	28.2	17.5	14.8	34.0	11.0×9.4	11.0×10.6	Distinctly less.
Minimum	......	...	109.4	68.0	40.6	47.4	21.2	23.0	14.8	10.6	31.4	10.0×9.0	10.8×9.8	
Maximum	......	...	125.8	81.0	52.0	62.0	29.4	30.6	17.5	15.2	34.6	11.0×10.6	11.0×11.6	
***Pan vetus* (pleistocene).**														
England	......	♀?	*120±	76.8	47.0	61.0	29.8	31.0	21.2	14.8	39.0	12.5×10.5†	13.0×11.0†	
***Homo heidelbergensis* (pleistocene).**														
Germany	......	...	120.5	92.2	58.8	61.4	30.7	34.6	23.0	19.0	35.8	11.8×11.4	12.6×12.2	
***Homo* sp. (recent).**														
			101.8	75.6	46.8	53.6	33.4	37.5	20.8	20.2	35.2	12.6×11.6	12.4×11.0	
			95.0	71.4	45.3	62.0	35.4	42.3	20.4	18.8	36.4	12.2×11.8	12.6×11.4	
			90.2	66.2	36.2	42.2	23.4	27.5	15.2	11.5	28.6	10.2×9.8	9.6×9.0	

* Estimated. Error probably less than 5 mm.
† Dr. Woodward's measurements are respectively: 11.5×9.5 and 12.0×10.0 mm. Apparently he took into consideration the flattened surface only.

Remarks.—Within the limits of the generic characters recent chimpanzees, like other great apes, show many variations the nature of which is imperfectly understood. Numerous species have been described[1] but their cranial peculiarities, if such exist, are not yet known. Among the skulls in the National Museum series I have been unable to find satisfactory characters by which to distinguish local forms.

Comparing the Piltdown mandible with those from Kameroon and French Congo I have found no constant features other than those already mentioned. That part of mandible in front of m_1 is, for instance, shorter than in the two African jaws figured on plate 1; but No. 174710 (pl. 5, fig. 2) from French Congo has this region fully as short and nearly as deep as the type. In *Pan vetus* the thickened area which extends downward on outer side of mandible in continuation of the base of the coronoid process is more prominent than in most African specimens. It contributes to the robustness of the jaw in that region, and stands out noticeably beyond the level of the lower edge when the mandible is viewed at a certain angle from above. In African specimens this thickening is usually not sufficient to project noticeably beyond the level of the angular margin, but in No. 176235 from southern Kameroon it does so almost as much as in *Pan vetus*. The angle of the jaw is more evenly rounded off in *Pan vetus* than in most African chimpanzees that I have seen. These usually show a slight concavity below the angular region and another, often the more pronounced of the two, above it. In No. 174710 (pl. 5, fig. 2) from French Congo a very slight wearing away of the edge of the bone such as appears to have taken place in the Piltdown jaw would exactly produce the outline of the type. The teeth appear to be more diagnostic than the jaw, as I have been unable to find any African specimen in which they equal those of *Pan vetus* in size.

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[1] See Elliot, Rev. Primates, vol. 3, pp. 229-254, June, 1913, and Matschie, Sitzungsber. Gesellsch. naturforsch. Freunde, Berlin, 1914, pp. 327-335, July, 1914.

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ANONYMOUS. A Palaeolithic Skull. The Times, London, November 23, 1912, p. 10.

Announcement that: Excavations in Sussex undertaken by an anthropological student have brought to light fragments of a human skull detailed description of which will be presented at a meeting of the Geological Society to be held on December 18.

ANONYMOUS. Discovery of Human Skull (Early Pleistocene?) near Lewes. Nature, vol. 90, p. 390. December 5, 1912.

A "note" announcing Mr. Dawson's discovery of the Piltdown remains.

ANONYMOUS. A Palaeolithic Skull. The Times, London, December 19, 1912, p. 4.

Principally an abstract of paper presented at meeting of Geological Society, December 18. No name printed.

ANONYMOUS. Palaeolithic Man. Nature, vol. 90, p. 438. December 19, 1912.

Brief synopsis of history and characters of Piltdown man. No name printed.

ANONYMOUS. The Piltdown Skull. Nature, vol. 91, pp. 640-641. August 21, 1913.

Account of the discussion by members of the anatomical section, International Congress of Medicine.

ANTHONY, R. Les restes humains fossiles de Piltdown (Sussex). Revue Anthropologique, vol. 23, pp. 293-306. September, 1913.

Accepts the association of the skull with jaw: "Ce qui pourrait le rendre vraisemblable c'est que, chez les jeunes Anthropoïdes nous voyons précisément associée à une boite crânienne sensiblement sphérique une mâchoire à menton fuyant," p. 304. Regards the formation of a new genus as not justified: "En raison de sa capacité cranienne toute humaine il me semble cependant contre-indiqué de le séparer du genre *Homo*. Le nom spécifique d'*Homo dawsoni* me semble devoir etre préfére à celui d' *Eoanthropus dawsoni* . . . ." (p. 305).

BOULE, MARCELLIN. L'Homme fossile de la Chapelle-aux-Saints. Annales de Paléontologie, vol. 6, pp. 111-172, 1911, vol. 7, pp. 21-56, 85-192, 1912, vol. 8, pp. 1-70. 1913.

Eoanthropus frequently mentioned, pp. 245-265, but at this time known to the author from descriptions only. (See next title.)

BOULE, MARCELLIN. La Paléontologie humaine en Angleterre. L'Anthropologie, vol. 26, pp. 1-67, figs. 1-21. April, 1915.

Eoanthropus, pp. 39-67. Accepts association of skull with jaw, though recognizing that jaw is exactly that of a chimpanzee, and that it would have been described as *Troglodytes dawsoni* if found alone (p. 60). Admits that the presence of a pliocene anthropoid ape in western Europe would be nothing extraordinary (p. 62). Regards the creation of a new genus as unnecessary. Criticizes Waterston's view that jaw did not belong with skull: "Cet argument, d'ordre purement anatomique, n'est donc pas sans valeur. Mais il a le tort d'etre imprégné d'un vieux parfum cuviérin et de reposer trop exclusivement sur les données morphologiques tirées de l'Homme actuel. Or, les paléontologistes savent combien la nature est fertile en combinaisons imprévues; elle a pu associer d'autant plus facilement un condyle et une fosse glénoïde d'Homme à une mâchoire de Singe que, mécaniquement et physiologiquement, cette association ne paraît pas absurde. Il semble que, dans l'évolution d'une tête osseuse, quand la face diminue, la mandibule diminue plus lentement, ne suivant en quelque sorte que de loin le mouvement de retrait" (p. 62).

DAWKINS, BOYD. [Discussion of the Piltdown skull.] Abstr. Proc. Geol. Soc. London, session 1912-13, pp. 23-24. December 28, 1912. (See also Quart. Journ. Geol. Soc. London, vol. 69, pp. 148-149. March, 1913, issued April 25, 1913.)

Accepts association of skull and jaw. Concludes that *Eoanthropus* is "a missing link between man and the higher apes, appearing at that stage of the evolution of the higher mammalia in which it may be looked for—in the pleistocene age. The modern type of man had no place in this age."

DAWSON, CHARLES, and WOODWARD, ARTHUR SMITH. On the discovery of a palaeolithic human skull and mandible in a flint-bearing gravel overlying the Wealden (Hastings Beds) at Piltdown, Fletching (Sussex). Abstr. Proc. Geol. Soc. London, session 1912-13, pp. 20-22. December 28, 1912.

Abstract of history and characters. Name not printed. ". . . . it may be regarded as representing a hitherto unknown genus and species, for which a new name is proposed."

DAWSON, CHARLES, and WOODWARD, ARTHUR SMITH. On the discovery of a palaeolithic human skull and mandible in a flint-bearing gravel overlying the Wealden (Hastings Beds) at Piltdown, Fletching (Sussex). Quart. Journ. Geol. Soc. London, vol. 69, pp. 117-124, pls. 15-21 (wash drawings; for photographs see Woodward, 1915), figs. 1-10. March, 1913. Read December 18, 1912; issued April 25, 1913.

DAWSON, CHARLES, and WOODWARD, ARTHUR SMITH. Supplementary note on the discovery of a palaeolithic human skull and mandible at Piltdown (Sussex). Abstr. Proc. Geol. Soc. London, session 1913-1914, pp. 28-29. December 31, 1913.

"In shape, the canine resembles the milk canine of man and that of the apes more closely than it agrees with the permanent canine of any known ape. In accordance with a well-known palaeontological law, it therefore approaches the canine of the hypothetical Tertiary Anthropoids more nearly than any corresponding tooth hitherto found."

DAWSON, CHARLES, and WOODWARD, ARTHUR SMITH. Supplementary note on the discovery of a palaeolithic human skull and mandible at Piltdown (Sussex). Quart. Journ. Geol. Soc. London, vol. 70, pp. 82-93, pls. 14-15, figs. 1-3. April 25, 1914.

"It results, therefore, from these comparisons that, among known Upper Tertiary and Recent Anthropoids, the permanent lower canine of *Eoanthropus* agrees more closely in shape with the milk-canine both of man and of the apes than with the corresponding permanent tooth in either of these groups. It is also obvious that the resemblance is greater between *Eoanthropus* and *Homo* than between the former and any known genus of apes. In other words, the permanent tooth of the extinct *Eoanthropus* is almost identical in shape with the temporary milk-tooth of the existing *Homo*. Hence it forms another illustration of the well-known law in mammalian palaeontology, that the permanent teeth of an ancestral race agree more closely in pattern with the milk teeth than with the permanent teeth of its modified descendants" (p. 91).

DUCKWORTH, DR. [Discussion of the Piltdown skull]. Abstr. Proc. Geol. Soc. London, session 1912-1913, p. 24. December 28, 1912. (See also Quart. Journ. Geol. Soc. London, vol. 69, p. 149. March, 1913. Issued April 25, 1913.)

"It was justifiable to associate the various fragments as parts of one human skull, and the presence of so many simian characters in one and the same specimen was a point of great significance."

ELLIOT, G. F. SCOTT. Prehistoric Man and His Story. London and Philadelphia, 1915, pp. I-XIV, 1-398, 64 illustr. and diagrams.

Piltdown woman, pp. 125-129. "The jaw in some respects resembles that of a young chimpanzee . . . . Though there are a few distinctively ape-like characters, most of those points in which the skull differs from modern man can be detected in one or another of the primitive races. If so, she is the only representative known of one of the very earliest strains of mankind, perhaps the very first known of the original 'generalized world-ranging type' from which all other varieties were derived" (pp. 128-129).

FORESTIER, A. Periods of Prehistoric Man: Pleistocene Types, Weapons and Tools. Illustrated London News, vol. 143, pp. 296-297. Numerous figures. August 23, 1913.

Accepts Keith's reconstruction of jaw.

GIUFFRIDA-RUGGERI, V. Dawson (Ch.) e Woodward (A. S.). On the discovery of a palaeolithic skull and mandible in a flint-bearing gravel overlying the Wealden (Hastings Beds) at Piltdown, Fletching (Sussex). Arch. Antrop. e Etnol., Firenze, vol. 43, pp. 184-186. 1913.

Review. Doubts the distinctness of the genus *Eoanthropus* from *Homo*. "In ogni caso sin d'ora appare che l' '*Eoanthropus*' non è un fossile ben chiaro, como nuovo genere, e che molto probabilmente rientrerà nei fossili già noti: forse il Gibraltar è il più vicino."

GREGORY, WILLIAM KING. The Dawn Man of Piltdown, England. Am. Mus. Journal, vol. 14, pp. 189-200, figs. 1-11. May, 1914.

Accepts association of skull with jaw. Compare fig. 5 with text fig. in present article.

HADDON, A. C. *Eoanthropus dawsoni*. Science, n. s. vol. 37, pp. 91-92. January 17, 1913.

HRDLIČKA, A. The most ancient skeletal remains of man. Ann. Rep. Smiths. Inst., 1913, pp. 491-552, pls. 1-41, figs. 1-12.

Eoanthropus, pp. 500-509. "It represents doubtless one of the most interesting finds relating to man's antiquity, though seemingly the last word has not yet been said as to its date and especially as to the physical characteristics of the being it stands for."

IRVING, A. Some recent work on later quarternary geology and anthropology, with its bearing on the question of "pre-boulder-clay man." Journ. Royal Anthrop. Inst. Gt. Brit. and Ireland, vol. 44, pp. 385-393. July-December, 1914.

"The hominid *Eoanthropus dawsoni* (Piltdown) is undoubtedly of pre-chalky boulder-clay age" (p. 393).

KEITH, A. [Discussion of the Piltdown skull.] Abstr. Proc. Geol. Soc. London, session 1912-13, p. 23. December 28, 1912. (See also Quart. Journ. Geol. Soc. London, vol. 69, p. 148. March, 1913. Issued April 25, 1913.)

Accepts association of skull with jaw but considers that reconstruction of jaw is made to be too much like chimpanzee.

KEITH, A. Ape-man or Modern Man? The two Piltdown skull reconstructions. Illustrated London News, vol. 143, p. 245, figs. 1-6. August 16, 1913.

Jaw reconstructed to hold a human dentition.

KEITH, A. Ape-man or Modern Man? The two Piltdown skull reconstructions. The case for Professor Arthur Keith's reconstruction. Illustrated London News, vol. 143, p. 282. August 23, 1913. 4 figures.

Reconstruction of jaw to resemble as nearly as possible that of *Homo*.

KEITH, A. The Piltdown Skull and Brain Cast. Nature, vol. 92, pp. 197-199, figs. 1-3. October 16, 1913.

KEITH, ARTHUR. The Piltdown Skull and Brain Cast. Nature, vol. 92, p. 292. November 6, 1913.

KEITH, ARTHUR. The Piltdown Skull and Brain Cast. Nature, vol. 92, pp. 345-346. November 20, 1913.

KEITH, A. [Discussion of new reconstruction of skull of *Eoanthropus.*] Abstr. Proc. Geol. Soc. London, session 1913-14, p. 30. December 31, 1913. (See also Quart. Journ. Geol. Soc. London, vol. 70, p. 98, April 25, 1914.)

Admits difficulties in associating jaw, skull and canine as parts of one individual, but regards all as representing one species: "Two other difficulties he had encountered were (1) the presence of a pointed projecting canine in the jaw and an articular eminence at the glenoid fossa of the skull; and (2) a much-worn canine tooth in a jaw in which the third molar tooth—according to the published X-ray photograph of the Piltdown mandible—was not completely erupted. (See Underwood, December 31, 1913.) He agreed that all three parts—skull, jaw, and canine tooth—must be assigned to *Eoanthropus,* but he was not convinced that they could all belong to the same individual."

KEITH, A. Problems relating to the teeth of the earlier forms of prehistoric man. Proc. Roy. Soc. Medicine, vol. 6, Odont. sect., pp. 103-119, figs. 1-10. 1913.

Piltdown mandible, pp. 116-119.

KEITH, ARTHUR. The Significance of the Discovery at Piltdown. Bedrock, vol. 2, pp. 435-453, figs. 1-3. January, 1914.

"There is one way out of this difficulty—that suggested by Sir E. Ray Lankester and urged by Professor Waterston—namely, that the mandible and skull are parts of different kinds of beings; the mandible that of some unknown anthropoid, and the skull that of a primitive form of man. When we seek to get out of our difficulty in this way we raise others. The molar teeth in the Piltdown mandible are essentially human in appearance; the texture of the mandible is similar to that of the skull. The markings for the temporal muscle, which acts on the jaw, are different to any ever seen in a human skull and indicate that the mandible should be of a peculiar character—such as has been found."

KEITH, ARTHUR. The reconstruction of fossil human skulls. Journ. Royal Anthrop. Isnt. Gt. Brit. and Ireland, vol. 44, pp. 12-31, figs. 1-16. January-June, 1914.

Describes process of reconstructing the Piltdown skull.

KEITH, ARTHUR. The Antiquity of Man. London and Philadelphia, 1915, (preface dated July), pp. I-XX, 1-519, 189 figures and diagrams.

Piltdown skull, pp. 293-511; the most elaborate discussion yet published. Account of mandible with special reference to simian features, pp. 430-452 (drawings reproduced in figs. 165 and 167 should be compared with photographs in present article). Account of teeth, pp. 453-457. Conclusions: "Thus in our scrutiny and reconstruction of the Piltdown mandible, although we have come across many details of structure which seem to suggest that it formed part of an anthropoid rather than a human being, we have met with no feature which clearly debars it from being placed with the skull . . . . our difficulties are infinitely greater if we try to allocate the skull to a human being and the mandible to an unknown kind of anthropoid (p. 453) . . . . Thus in the manner in which it has become worn by use the Piltdown canine differs from all known human and anthropoid [mandibular] teeth (p.

459). The molar teeth leave us in no doubt; they are human. If the question is asked: What are the characters of these teeth which are so essentially human? it must be confessed that a direct and explicit answer is not easily returned . . . . However we may waver about the Piltdown mandible, the clear direct evidence of the molar teeth comes ever to our aid" (pp. 469-470). Places *Eoanthropus* on a line distinct from those leading to *Homo heidelbergensis* and *H. neanderthalensis* on the one hand and to modern man on the other (p. 501). (See Pilgrim and Sutcliffe.) "That we should discover such a race [human, with canine teeth pointed, projecting, and shaped as in anthropoid apes], has been an article of faith in the anthropologist's creed ever since Darwin's time" (p. 459). Received too late for notice in body of text.

LANKESTER, RAY. [Discussion of the Piltdown skull.] Abstr. Proc. Geol. Soc. London, session 1912-13, pp. 22-23. December 28, 1912. (See also Quart. Journ. Geol. Soc. London, vol. 69, pp. 147-148. March, 1913. Issued April 25, 1913.)

"He did not consider it certain that the lower jaw and the skull belonged to the same individual."

MACCURDY, G. G. Ancestor Hunting: the Significance of the Piltdown Skull. Amer. Anthrop. n. s. vol. 15, pp. 248-256. April-June, 1913.

MOIR, J. REID. The Piltdown Skull. The Times, London, December 25, 1912, p. 8.

"In my opinion, then, Mr. Dawson is to be congratulated on having made the immensely important discovery of the remains of one of the beings who made the eolithic flint implements." (See Sutcliffe.)

MUNRO, ROBERT. Prehistoric Britain (Home University of Modern Knowledge), pp. I-VI, 1-256, figs. 1-24. 1913.

Eoanthropus, pp. 25, 52-55, 70-74, figs. 8-9. Accepts association of skull with jaw.

NEHRING, A. Ueber einen menschlichen Molar aus dem Diluvium von Taubach bei Weimar. Zeitschr. für Ethnologie, vol. 27, pp. 573-577, figs. 1-4. October, 1895.

The author regards this tooth as human, but is unable to compare it with anything except the first lower molar of a chimpanzee. According to the figures it almost exactly resembles the corresponding tooth of *Pan vetus.* Size not so great: 11.7 x 9.9 mm. In the actual specimen the similarity to m_1 of *Pan* is said to be still greater than in the drawing.

PILGRIM, GUY E. New Siwalik primates and their bearing on the evolution of man and the Anthropoidea. Rec. Geol. Surv. India, vol. 45, pp. 1-74, pls. 1-4, figs. 1-2.

Accepts association of skull with jaw and places *Eoanthropus* on line leading to *Homo neanderthalensis.* (See Keith, 1915, and Sutcliffe.)

PUCCIONI, NELLO. Appunti intorno al frammento mandibolare fossile di Piltdown (Sussex). Archivio per l'Antropologia e la Etnologia, vol. 43, pp. 167-175. 1913.

Jaw and skull not from one individual. Jaw more like Neanderthal man than like chimpanzee. "Mi sembra pertanto indubitabile che la mandibola in questione appartenga ad un tipo rozzo, a mio parere più simile al tipo di Neanderthal che non al *Troglodites* e mi sembra altresì che non si possa considerare probabile che i caratteri grossolani di questa mandibola si accompagnassero ai caratteri relativamente fini (assenza dell arcate sopraorbitarie, fronte alta e dritta ecc.) dei frammenti cranici che le furono rinvenuti accanto: ond'é, che concordemente a quanto pensano due eminenti scienziati inglesi (il Lankester e il Waterston), io sono di opinione che la mandibola ed il cranio abbiano probabilmente appartenuto a due individui distinti" (p. 175).

PUCCIONI, NELLO. Morphologie du maxillaire inférieur. L'Anthropologie, vol. 25, pp. 291-321, figs. 1-3. 1914.

Reaffirms view that Piltdown mandible is less simian than Smith Woodward makes it appear (p. 315).

PYCRAFT, W. P. The most ancient inhabitant of England: the newly-found Sussex Man. Illustrated London News, vol. 141, p. 958. December 28, 1912.

PYCRAFT, W. P. Ape-Man or Modern Man? The two Piltdown skull reconstructions. The case for Dr. A. Smith Woodward's reconstruction. Illustrated London News, vol. 143, p. 282. August 23, 1913. Four figures.

"But no one competent to express an opinion would accept this interpretation [that skull is man and jaw ape]."

ROBINSON, LOUIS. The Story of the Chin. Knowledge n. s., vol. 10, pp. 410-420. November, 1913. (Reprinted in Smithsonian Report for 1914, pp. 599-609, pls. 1-12, 1915.)

Piltdown jaw (symphyseal region) figured (pl. 7) but not mentioned in the text.

SCHWALBE, G. Kritische Besprechung von Boule's Werk: "L'Homme fossile de la Chapelle-aux-Saints." Zeitschr. für Morphologie und Anthropologie, vol. 16, pp. 227-610. January 31, 1914.

Piltdown skull and jaw, pp. 603-4. Not willing to accept the suggestion that skull and jaw did not belong to one individual, but considers the facts too uncertain to form basis of positive opinion.

SHATTOCK, S. G. Morbid thickening of the calvaria; and the reconstruction of bone once abnormal; a pathological basis for the study of the thickening observed in certain pleistocene crania. Seventeenth International Congress of Medicine, London, 1913, sect. 3, pt. 2, pp. 3-46, pls. 1-4, text figs. 1-3. 1914.

Piltdown skull, pp. 42-46. "But to conclude. Without making any dogmatic statement, certain details of the Piltdown calvaria suggest the possibility of a pathological process having underlain the thickened condition" (p. 46). Accepts association of skull with jaw, and regards the third lower molar as unerupted (p. 43). See Underwood, December 31, 1913.

SMITH, G. ELLIOT. Appendix [to paper by Dawson and Woodward]. Abstr. Proc. Geol. Soc. London, session 1912-13, p. 22. December 28, 1912.

Abstract of paper mentioned under next title. The last paragraph of abstract does not occur in full account. It is: "There are no grounds whatever for supposing that this simian jaw and human brain-cast did not belong to one and the same individual, who was probably a right-handed female."

SMITH, GRAFTON ELLIOT. Preliminary report on the cranial cast [of the Piltdown skull]. Quart. Journ. Geol. Soc. London, vol. 69, pp. 145-147. March, 1913. Issued April 25, 1913.

SMITH, G. ELLIOT. The Piltdown Skull. Nature, vol. 92, p. 131. October 2, 1913.

Accepts association of skull with jaw and adds: "The small and archaic brain and thick skull are undoubtedly human in character, but the mandible, in spite of the human molars it bears, is more simian than human. So far from being an impossible combination of characters, this association of brain and simian features is precisely what I anticipated in my address to the British Association at Dundee (Nature, September 26, 1912, p. 125), some months before I knew of the existence of the Piltdown skull, when I argued that in the evolution of man the development of the brain must have led the way. The

growth in intelligence and in the powers of discrimination no doubt led to a definite cultivation of the aesthetic sense, which, operating through sexual selection, brought about a gradual refinement of the features."

SMITH, G. ELLIOT. The Piltdown Skull and Brain Cast. Nature, vol. 92, pp. 267-268. October 30, 1913.

SMITH, G. ELLIOT. The Piltdown Skull and Brain Cast. Nature, vol. 92, pp. 318-319. November 13, 1913.

SMITH, G. ELLIOT. The controversies concerning the interpretation and meaning of the remains of the dawn-man found near Piltdown. Nature, vol. 92, pp. 468-469. December 18, 1913.

"There is definite internal evidence that the jaw is not really an ape's; the teeth it bears are human . . . ."

SMITH, G. ELLIOT. On the exact determination of the median plane of the Piltdown skull. Abstr. Proc. Geol. Soc. London, session 1913-14, p. 29, December 31, 1913. (See also Quart. Journ. Geol. Soc. London, vol. 70, pp. 93-97, figs. 4-6, April 25, 1914.)

SMITH, G. ELLIOT. The controversies concerning the interpretation and meaning of the remains of the dawn-man found near Piltdown. Mem. and Proc. Manchester Lit. and Philos. Soc., vol. 58, pp. VII-IX. March 31, 1914.

"That the jaw and cranial fragments . . . . belonged to the same creature there had never been any doubt on the part of those who have seriously studied the matter" (p. VIII). The author believes that: "When man was first evolved the pace of evolution must have been phenomenally rapid." He alludes to "the turmoil incident to the inauguration of the Pleistocene Period." (p. IX).

SMITH, G. ELLIOT. The Significance of the Discovery at Piltdown. Bedrock, vol. 3, pp. 1-17. April, 1914.

A detailed criticism of Professor Keith's views.

SOLLAS, W. J. Ancient Hunters and their Modern Representatives. Ed. 2, London, 1915, pp. I-XIV, 1-591, 314 figs.

Piltdown man, pp. 49-56. "Some have regarded such a being as an improbable monster and have suggested that the jaw may not have belonged to the skull, but to a true ape. The chances against this are, however, so overwhelming that the conjecture may be dismissed as unworthy of serious consideration. Nor on reflection need the combination of characters presented by *Eoanthropus* occasion surprise. It had, indeed, been long previously anticipated as an almost necessary stage in the course of human development" (p. 54).

SUTCLIFFE, W. H. A criticism of some modern tendencies in prehistoric anthropology. Mem. & Proc. Manchester Lit. and Philos. Soc., vol. 57, no. 7, pp. 1-25, pls. 1-2. June 24, 1914.

Skull and jaw "undoubtedly belonging to the same individual." *Eoanthropus* placed on line leading to *Homo sapiens,* pl. 1. (See Keith, 1915, and Pilgrim.) Eoliths produced by natural agencies. (See Moir.)

THACKER, A. G. The Significance of the Piltdown Discovery. Science Progress, vol. 8, pp. 275-290. October, 1913.

Accepts association of skull with jaw.

TYRELL, G. W. The Sussex Skull. Knowledge, vol. 36, p. 61, February, 1913.

Account of paper by Dawson and Woodward. Name *Eoanthropus* not printed.

UNDERWOOD, ARTHUR S. The Piltdown Skull. British Journal of Dental Science, vol. 56, pp. 650-652, 3 plates (not numbered). October 1, 1913.

Accepts association of skull with jaw, but shows by means of radiographs the exact similarity of the jaw to that of a chimpanzee. Does not especially discuss the characters of the molars.

UNDERWOOD, A. S. [Discussion of "Supplementary Note" on Piltdown skull.] Abstr. Proc. Geol. Soc. London, session 1913-14, pp. 30-31. December 31, 1913. (See also Quart. Journ. Geol. Soc. London, vol. 70, p. 99. April 25, 1914.)

"The sockets of the third molar were not those of an erupting tooth, the roots had been quite completed, and the tooth was in its final position at death." (See Keith, December 31, 1913.)

VRAM, U. G. Le reconstruzioni dell' Eoanthropus Dawsoni, Woodward. Boll. Soc. Zool. Ital., Roma, ser. 3, vol. 2, pp. 195-198. 1913.

Accepts association of jaw with skull, but considers that a new species should not have been based on such incomplete material.

WALKHOFF, DR. Entstehung und Verlauf der phylogenetischen Umformung der menschlichen Kiefer seit dem Tertiär und ihre Bedeutung für die Pathologie der Zähne. Deutsche Monatsschr. für Zahnheilkunde, vol. 31, pp. 947-979, figs. 1-9. December, 1913.

Piltdown jaw, pp. 971-979. Accepts association of skull and jaw. Regards the jaw as a confirmation of his views on the origin of the chin. "Das Kieferbruchstück von Piltdown wird damit zu einem neuen, sehr wichtigen Beweise für meine Theorie der Kinnbildung, nach welcher eine Reduktion des gesammten Kiefers, insbesondere aber des Kieferkörpers in dorsaler Richtung stattfand mit Ausnahme der vorderen Basalpartie, welche unter dem Einfluss der Muskeln steht, die bei der artikulierten Sprache tätig sind" (p. 974).

WATERSTON, PROF. [Discussion of the Piltdown skull.] Abstr. Proc. Geol. Soc. London, session 1912-13, p. 25. December 28, 1912. (See also Quart. Journ. Geol. Soc. London, vol. 69, p. 150. March, 1913. Issued April 25, 1913.)

Very difficult to believe that the two specimens could have come from the same individual.

WATERSTON, DAVID. The Piltdown Mandible. Nature, vol. 92, p. 319, figs. 1-3. November 13, 1913.

Compares with chimpanzee and concludes that ". . . . it seems to me to be as inconsequent to refer the mandible and the cranium to the same individual as it would be to articulate a chimpanzee foot with the bones of an essentially human thigh and leg."

WOODWARD, A. SMITH. The Piltdown Skull. Brit. Med. Journ., vol. 2 for 1913, p. 762. September 20, 1913.

Abstract of lecture before the British Association at Birmingham on September 16. Announcement of discovery of canine tooth (see also next title). "As to the question whether the ape-like mandible belonged to the skull, it could only be said that its molar teeth were typically human, its muscle markings such as might be expected, and that it was found in the gravel near the skull." "The Piltdown man might . . . . well have been the direct ancestor of modern man, connecting him with the undiscovered tertiary apes, whose rounded skulls must have resembled those of the immature young of existing apes."

WOODWARD, A. SMITH. The Piltdown Skull. Nature, vol. 92, pp. 110-111. September 25, 1913.

Abstract of lecture before the British Association at Birmingham on September 16. Announcement of discovery of canine tooth. "This tooth corresponds exactly in shape with the lower canine of an ape, and its worn face shows that it worked upon the upper canine in the true ape fashion."

WOODWARD, A. SMITH. Note on the Piltdown Man (*Eoanthropus dawsoni*). Geol. Mag. n. s., dec. 5, vol. 10, pp. 433-434, pl. 15. October, 1913.

WOODWARD, A SMITH. A Guide to the Fossil Remains of Man in the British Museum, pp. 1-33, pls. 1-4, figs. 1-12. 1915.

Contains photographs of the Piltdown remains (pls. 1-4). These should be compared with the wash drawings in Dawson and Woodward, April 25, 1913, particularly as regards the teeth.

EXPLANATION OF PLATES

PLATE 1

All figures about ¾ natural size. Casts.

FIG. 1. *Pan* sp. Africa: no exact locality. No. 84655, U. S. National Museum.
FIG. 2. *Pan vetus*, England: Piltdown.
FIG. 3. *Pan* sp. Africa: French Congo. No. 174700, U. S. National Museum.

The casts of the African specimens have been mutilated as nearly as possible in the same manner as the fossil.

PLATE 2

All figures about ¾ natural size. Casts, except nos. 1″, 2″ and 4.

FIG. 1. *Pan* sp. Africa: no exact locality. No. 84655, U. S. National Museum.
FIG. 2. *Pan vetus*, England: Piltdown.
FIG. 3. *Pan* sp. Africa: French Congo. No. 174700, U. S. National Museum.
FIG. 4. *Pan* sp. Africa: southern Kameroon. No. 176226, U. S. National Museum.

Fig. 2″ is copied from the photograph published by Dr. Woodward in the Guide to Fossil Remains of Man in the British Museum, pl. 4. Note that enamel on lingual side of metaconid has flaked off from m_1 in fig. 4.

PLATE 3

Skull greatly reduced, mandible about ¾ natural size.

Homo sp. Skull, North American Indian, No. 262540, U. S. National Museum; mandible, Mongolian, No. 278783, U. S. National Museum.

To show the association of cranial and mandibular characters normal in the *Hominidæ*.

PLATE 4

Skull greatly reduced, mandible about ¾ natural size.

Pan sp. African: southern Kameroon. No. 176226, U. S. National Museum.

To show the association of cranial and mandibular characters normal in the *Pongidae*.

PLATE 5

All figures about ⅔ natural size. Nos. 1 and 3 from casts.

Mandible of four adult individuals of recent *Pan* to show individual variation. Note particularly the symphysis, the sigmoid notch and the angular region.

FIG. 1. *Pan* sp. Africa: no exact locality. No. 84655, U. S. National Museum.
FIG. 2. *Pan* sp. Africa: French Congo. No. 174710, U. S. National Museum.
FIG. 3. *Pan* sp. Africa: French Congo. No. 174700, U. S. National Museum.
FIG. 4. *Pan* sp. Africa: southern Kameroon. No. 176244, U. S. National Museum. (Coronoid process restored.)

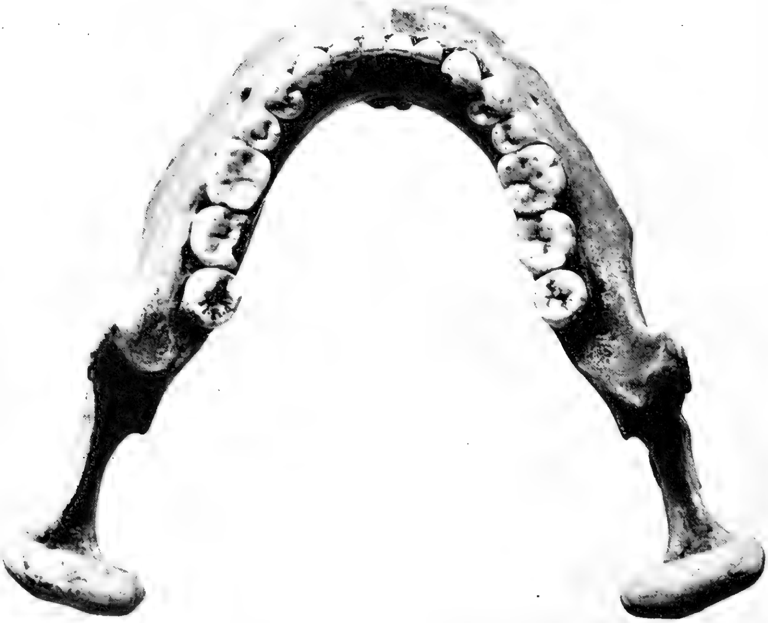
1

2

3

1 and 3, PAN SP. AFRICA (RECENT), $\times \frac{3}{4}$
2, PAN VETUS. ENGLAND (PLEISTOCENE), $\times \frac{3}{4}$
The casts of the African specimens have been mutilated as nearly as possible in the same manner as the fossil

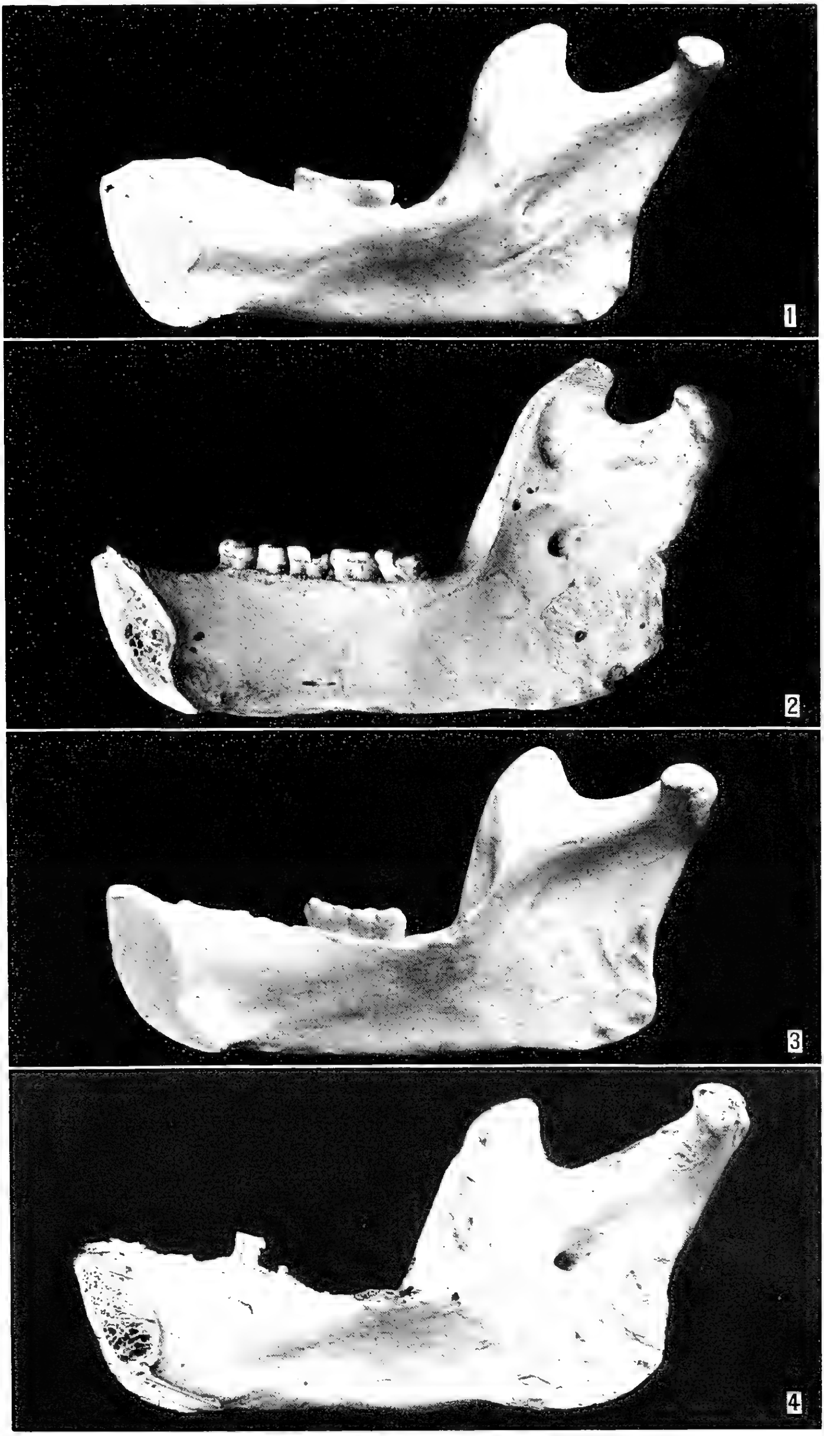
1, 3, and 4, PAN SP. AFRICA (RECENT), $\times \frac{3}{4}$
2, PAN VETUS. ENGLAND (PLEISTOCENE), $\times \frac{3}{4}$
The casts of the African specimens have been mutilated as nearly as possible in the same manner as the fossil



HOMO SP. (RECENT). SKULL GREATLY REDUCED, MANDIBLE × $\frac{3}{4}$
To show the association of cranial and mandibular characters normal in the Hominidæ

PAN SP. (RECENT) SKULL GREATLY REDUCED, MANDIBLE × $\frac{3}{4}$

To show the association of cranial and mandibular characters normal in the Pongidæ



PAN SPP. (RECENT), $\times \frac{2}{3}$

To show variations in form of mandible

SMITHSONIAN MISCELLANEOUS COLLECTIONS
VOLUME 65, NUMBER 13

Descriptions of Seven New Subspecies and One New Species of African Birds (Plantain-Eater, Courser, and Rail)

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DESCRIPTIONS OF SEVEN NEW SUBSPECIES AND ONE NEW SPECIES OF AFRICAN BIRDS (PLANTAIN-EATER, COURSER, AND RAIL)

By EDGAR A. MEARNS

ASSOCIATE IN ZOOLOGY, UNITED STATES NATIONAL MUSEUM

This is the author's thirteenth publication devoted to descriptions of new forms of African birds. Three of the forms here described are from the collection made by the Paul J. Rainey African Expedition, 1911-12; three are from the Smithsonian African Expedition, 1909-10 collection, made under the direction of Col. Theodore Roosevelt; one is from the collection of the Childs Frick African Expedition, 1911-12; and one is from the African collection made for the Museum of Comparative Zoology at Cambridge, Massachusetts, by Dr. Glover M. Allen, in the year 1909. The names of special tints and shades of colors used in this paper conform to Robert Ridgway's "Color Standards and Color Nomenclature," issued March 10, 1913. All of the measurements were taken, in millimeters, by Miss Celestine B. Hodges.

TURACUS HARTLAUBI (Fischer and Reichenow)

Hartlaub's Plantain-eater

Corythaix Hartlaubi FISCHER and REICHENOW, Journ. für Ornith., 1884, p. 52 (base of Mount Meru, near Kilimanjaro, Masai Land, German East Africa).

Hartlaub's Plantain-eater has never been divided into its component subspecies, because of the assumption that it does not vary geographically. It is apparent, however, on spreading out sixty-four specimens from various parts of the range of the species, that there are four easily-recognizable geographical forms, three of which are characterized beyond. The four subspecies may be recognized by means of the following

KEY TO THE SUBSPECIES OF *Turacus hartlaubi* (FISCHER and REICHENOW)

a. Thighs and crissum black.............*Turacus hartlaubi crissalis* (p. 3)
aa. Thighs and crissum varying from greenish violet-gray to blackish violet-gray.
  b. Wings and back dark bluish violet
Turacus hartlaubi hartlaubi (p. 2)
  bb. Wings and back helvetia blue or antwerp blue.
    c. Anterior under parts, sides of face, neck, and upper back cerro green; red portion of wing-quills pomegranate purple above, pansy purple below
Turacus hartlaubi medius (p. 3)
    cc. Anterior under parts, sides of face, neck, and upper back calla green; red portion of wing-quills spectrum red above, amaranth purple below
Turacus hartlaubi cærulescens (p. 4)

In this species the sexes are practically alike in color and size,[1] the differences between the subspecies being in color alone. There is considerable individual variation in size. The coloration is affected by wearing and fading as the result of attrition, sunlight, and soaking rains. Color change is most apparent on the red feathering of the wing-quills, and, naturally, is more marked on the upper or exposed side than on the under surface. When the birds are in freshly-assumed plumage the green color extends farther backwards upon the upper back, the color being imparted to this part by green filamentous tips to the feathers; when these green tips have been worn away, the underlying color becomes exposed, and then the bluish coloring extends higher upon the back. Despite the differences which are due to the causes noted above, no difficulty is experienced in separating the four geographical forms. In the following diagnoses the race characters of the subspecies are presented in consecutive order:

TURACUS HARTLAUBI HARTLAUBI (Fischer and Reichenow)

Hartlaub's Plantain-eater

Corythaix Hartlaubi FISCHER and REICHENOW, Journ. für Ornith., 1884, p. 52 (Meru Mountain, near Mount Kilimanjaro, German East Africa).

Subspecific characters.—Wings and back dark bluish violet; anterior under parts, sides of face, neck, and upper back spinach green, much mixed with subterminal blue spots on the latter; upper side of head dark violet-blue; upper surface of red portion of wings violet-

[1] Females average a trifle smaller than males.

carmine, lower surface dahlia purple; upper side of tail blackish violet, paler on outer webs of lateral rectrices; thighs and crissum violet-gray with a slight admixture of green to the feather-tips.

Average measurements of two adult males from Mount Kilimanjaro.—Wing, 168.5; tail, 185; culmen (chord), 23; tarsus, 39.2.

Average measurements of five adult females from Mount Kilimanjaro (4,000 to 7,000 feet).—Wing, 164; tail, 182; culmen (chord), 21.5; tarsus, 39.1.

Geographical range.—From the Meru and Kilimanjaro mountains, on the east, westward across German East Africa, and into British East Africa in the hills of the Sotik District, on the headwaters of the Southern N'guasso Nyiro River (Ngare Narok River), in the southwestern part of British East Africa.

Remarks.—The original form *hartlaubi* differs from all of the others in having a more saturated coloration.

TURACUS HARTLAUBI MEDIUS, new subspecies

Mount Kenia Plantain-eater

Type-specimen.—Adult female, Cat. No. 214870, U. S. Nat. Mus.; collected on Mount Kenia at 10,000 feet altitude, British East Africa, October 4, 1909, by Edgar A. Mearns. (Original number, 17008.)

Subspecific characters.—Wings and back helvetia blue; anterior under parts, sides of face, neck, and upper back cerro green, with less admixture of blue to the feathering of the upper back than in the typical form; upper side of head dark violet-blue; upper surface of red portion of wings pomegranate purple, lower surface pansy purple; upper side of tail cyanine blue, darker on middle pair of rectrices; thighs and crissum blackish violet-gray.

Measurements of type (adult female).—Wing, 176; tail, 188.5; culmen (chord), 23; tarsus, 39.5.

Average measurements of five adult male topotypes.—Wing, 169; tail, 187; culmen (chord), 22.3; tarsus, 39.7.

Average measurements of seven adult female topotypes.—Wing, 168; tail, 184.5; culmen (chord), 22.5; tarsus, 38.7.

Geographical range.—Forested highlands, north of the Uganda Railway, from Machacos to Lake Victoria.

TURACUS HARTLAUBI CRISSALIS, new subspecies

Crissal Plantain-eater

Type-specimen.—Adult female, Cat. No. 217621, U. S. Nat. Mus.; collected on Mount Mbololo, east of Mount Kilimanjaro, latitude 3°

South, altitude 4,000 feet, British East Africa, November 9, 1911, by Edmund Heller. (Original number, 418.)

Subspecific characters.—Wings and back azurite blue; anterior under parts, sides of face, neck, and upper back yellowish oil green, the upper back but slightly mixed with blue-tipped feathers;[1] upper side of head blackish green-blue; upper surface of red portion of wings carmine, lower surface aster purple; upper side of tail blackish azurite blue, brightening to azurite on outer webs of lateral rectrices; thighs and crissum black.

Measurements of type (adult female).—Wing, 161; tail, 188; culmen (chord), 20; tarsus, 37.

Geographical range.—Known only from the type-locality—the forested summit of Mount Mbololo, east of Mount Kilimanjaro, in British East Africa.

TURACUS HARTLAUBI CÆRULESCENS, new subspecies

Mount Gargues Plantain-eater

Type-specimen.—Adult male, Cat. No. 217620, U. S. Nat. Mus.; collected on Mount Gargues (North Creek), at 6,000 feet altitude, British East Africa, August 28, 1911, by Edmund Heller. (Original number, 271.)

Subspecific characters.—Wings and back antwerp blue; anterior under parts, sides of face, neck, and upper back calla green, with very little admixture of blue to the plumage of the upper back; upper side of head dark violet-blue; upper surface of red portion of wings spectrum red, lower surface amaranth purple; upper side of tail marine blue, paling to antwerp blue on outer webs of lateral rectrices; thighs and crissum dusky green-gray.

Measurements of type (adult male).—Wing, 167; tail, 187; culmen (chord), 21; tarsus, 37.5.

Average measurements of six adult male topotypes.—Wing, 168.1; tail, 185.9; culmen (chord), 22.5; tarsus, 38.2.

Average measurements of five adult female topotypes.—Wing, 166; tail, 182.4; culmen (chord), 22.8; tarsus, 38.8.

Geographical range.—Forested summit of Mount Gargues, from 6,000 to 7,100 feet (about twenty miles north of the Northern Guaso Nyiro River), in British East Africa.

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[1] When the green filamentous tips of the feathering of the upper back are worn away by attrition the subterminal blue becomes exposed.

CORYTHÆOLA CRISTATA YALENSIS, new subspecies

Yala River Plantain-eater

Type-specimen.—Adult male, Cat. No. 217630, U. S. Nat. Mus.; collected on the Yala River, British East Africa, February 7, 1911, by Edmund Heller. (Original number, 454.)

Subspecific characters.—Larger than *Corythæola cristata cristata* (Vieillot); upper parts paler and more greenish blue; forehead, around base of bill, with a broader band of pale bluish.

Measurements of type (adult male).—Wing, 335; tail, 380; culmen (chord), 43; tarsus, 57.

Average measurements of two adult males (type, and topotype No. 217628, U. S. Nat. Mus.)—Wing, 235.5; tail, 389; culmen (chord), 42.3; tarsus, 58.

Measurements of one adult female topotype (Cat. No. 217629, U. S. Nat. Mus.).—Wing, 338; tail, 393; culmen (chord), 39; tarsus, 54.

CURSORIUS GALLICUS MERUENSIS, new subspecies

Meru Courser

? *Cursorius somalensis* Lönnberg, Kungl. Sv. Vet. Akad. Handlingar, 47, No. 5, 1911, p. 37 (Lekiundu River, British East Africa).

Type-specimen.—Adult female, Cat. No. 56130, Museum of Comparative Zoology, Cambridge, Massachusetts; collected on plains by the Meru River, northern base of Mount Kenia, British East Africa, August 10, 1909, by Dr. Glover M. Allen. (No original number.)

Subspecific characters.—A member of the *Cursorius gallicus* group, most closely related to *Cursorius gallicus littoralis* Erlanger, from which it differs in being darker and more drabish in color. It requires no close comparison with *C. g. somalensis* Shelley, which is so much paler, and less grayish above, as to be instantly distinguished.

Description of type (adult female).—Forehead and crown anteriorly antique brown, passing into gray (dark gull gray) on the occiput; two black lines extend backwards from the eye, beginning at the upper and lower border, respectively, the upper black band joining the one from the opposite side on the upper nape, the lower one broadening posteriorly and ending on the side of the neck, the two black bands enclosing a triangular area of white; a whitish stripe also extends backwards from the angle of the mouth, below the eye, to include the upper half of the ear-coverts, below which the

side of the head is pale clay color; chin and throat soiled white; back, rump, upper tail-coverts, scapulars, and wing-coverts grayish wood brown; primaries black, the three innermost narrowly tipped with pure white; rectrices light drab, the external feather edged externally and broadly tipped with white, the next feather narrowly tipped with white; breast, upper abdomen, and sides light drab; axillars soiled white; under wing-coverts light drab, except those bordering the edge of the wing which form a band of slate color; lower abdomen and crissum soiled white.

Measurements of type (adult female).—Length of skin, 190; wing, 130; tail, 52; culmen (chord), 24; tarsus, 54.

Remarks.—The geographical forms of *Cursorius gallicus* (Gmelin) have been elucidated and figured by Erlanger[1] and Zedlitz.[2]

CURSORIUS TEMMINCKII JEBELENSIS, new subspecies

Jebel River Courier or Courser

Type-specimen.—Adult male, Cat. No. 216167, U. S. Nat. Mus.; collected at "Rhino Camp," Lado Enclave, on the left (west) bank of the Bahr-el-Jebel, latitude 2° 55′ North, some fifteen miles north of Wadelai on Albert Nyanza, in the Egyptian Sudan, Africa, January 11, 1910, by Edgar A. Mearns. (Original number, 17991.)

Characters.—Smaller than *Cursorius temminckii temminckii* Swainson;[3] general color of upper parts darker, also differing from *temminckii* in the following particulars: upper side of head tawny instead of ochraceous-tawny; upper side of neck, mantle, back, rump, upper tail-coverts, middle pair of rectrices, wing-coverts, and exposed portion of inner secondaries buffy brown instead of wood brown; upper breast light drab, of precisely the same shade as in *Cursorius gallicus meruensis,* described above, instead of avellaneous; lower chest with only a trace of the tawny color anterior to the black abdominal center.

Measurements of the type (adult male).—Length of skin, 175; wing, 114; tail, 42; culmen (chord), 20; tarsus, 37.5.

Average measurements of two adult males of Cursorius temminckii temminckii (from the Loita Plains, Southern N'guasso Nyiro

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[1] Journ. für Ornith., 1905, pp. 56-58, pl. 1.

[2] Journ. für Ornith., 1910, pp. 306, 307, pl. 6.

[3] *Cursorius Temminckii* Swainson, Zoological Illustrations, Vol. 2, 1822, pl. 106, described on the succeeding page ("arid tracts of Africa, at a distance from the sea"). Swainson's colored figure was made from a specimen in the Leadbeater collection, which perhaps came from South Africa.

River, Sotik District, British East Africa).—Wing, 120; tail, 48; culmen (chord), 19; tarsus, 40.5.

Average measurements of two adult females of Cursorius temminckii temminckii (same locality as above).—Wing, 117; tail, 44; culmen (chord), 19; tarsus, 38.

Remarks.—Unquestionably the bird figured by Swainson in Zoological Illustrations, Vol. 2, 1822, plate 106, and described on the succeeding page, is the same as a series of five specimens obtained by us in the Sotik District of British East Africa, east of Lake Victoria; and Mr. C. H. B. Grant's three specimens, one from the Lemek Valley, and two from Kamchuru, in the Lobor District, British East Africa, north of Lake Victoria, commented on by him in "The Ibis," 1915, page 60, belong to the same dark, typical form of *Cursorius temminckii* Swainson. In his Birds of Western Africa, Vol. 2, p. 230, pl. 24, Swainson described and figured a pale-colored form of this species, under the name *Tachydromus Senegalensis* Lichtenstein, from West Africa. Both of these forms are subspecifically distinct from that described above.

RHINOPTILUS AFRICANUS RAFFERTYI, new subspecies [1]

Abyssinian Courser

Type-specimen.—Adult male, Cat. No. 243063, U. S. Nat. Mus.; collected at the Iron Bridge, Hawash River, Abyssinia, February 4, 1912, by Edgar A. Mearns. (Original number, 20081.)

Subspecific characters.—Most closely related to *Rhinoptilus africanus hartingi* Sharpe and *R. a. bisignatus* (Hartlaub). From *hartingi* it differs in being very much darker in coloration, with general color of crown blackish instead of cinnamon-buff, and with the pale tips to the rectrices crossed by a subterminal blackish bar which is absent in *hartingi;* from *bisignatus* it differs in being much less ochraceous above and below, with narrower and paler margins to the feathers of the upper parts, and with narrower transverse black pectoral bands; and from both *hartingi* and *bisignatus* it may be instantly distinguished by the grayness of its upper parts.

Measurements of type (adult male).—Length of skin, 185; wing, 145; tail, 63; culmen (chord), 14; tarsus, 46.

Material.—Two males from the Hawash Valley, taken January 25 and February 4, 1912.

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[1] Named in honor of Dr. Donald G. Rafferty, a member of the Childs Frick African Expedition, who first drew my attention to this Courser, in the Hawash Valley.

Remarks.—I can find no previous name applicable to the present subspecies. Following is a list of the names which have been proposed for the whole species *africanus;* those preceded by an asterisk (*) are currently recognized as valid subspecies:

*Africanus (*Cursorius*) Temminck, 1807. Cat. Syst. Cab. d'Orn., 1807, pp. 175, 263 (Namaqualand, Southwestern Africa).

Collaris (*Tachydromus*) Vieillot, 1817. N. Dict. d'Hist. Nat., Vol. 8, 1817, p. 293 (Africa).

Bicinctus (*Cursorius*) Temminck, 1829. Man. d'Orn., Vol. 2, 1829, p. 515 (Interior of Africa).

Grallator (*Cursorius*) Leadbeater, 1830. Trans. Linn. Soc., N. S., Vol. 16, 1830, read December 20, 1825, p. 92 (type-locality not mentioned).

*Bisignatus (*Cursorius*) Hartlaub, 1865. Proc. Zool. Soc. London, 1865, p. 87 (Benguela, Angola).

*Gracilis (*Cursorius*) Fischer and Reichenow, 1884. Journ. für Ornith., 1884, p. 178 (Masailand).

*Hartingi (*Rhinoptilus*) Sharpe, 1893. Bull. Brit. Orn. Club, Vol. 3, 1893, p. xiv (Somaliland, East Africa).

*Sharpei (*Rhinoptilus africanus*) Erlanger, 1905. Journ. für Ornith., 1905, p. 59 (type-locality not given, but fixed by C. H. B. Grant,[1] who designated Deelfontein, central Cape Colony, as the particular type locality).

*Raffertyi (*Rhinoptilus africanus*) Mearns, 1915. Smithsonian Miscellaneous Collections, Vol. 65, No. 13, 1915, p. 7 (Iron Bridge, Hawash Valley, Abyssinia).

SAROTHRURA LORINGI, new species

Loring's Rail or Crake

Type-specimen.—Adult female, Cat. No. 214680, U. S. Nat. Mus.; collected on the west side of Mount Kenia, at the altitude of 8,500 feet, in British East Africa, October 13, 1909, by J. Alden Loring. (Original number, 439.)

Characters.—This form belongs to the group including *Sarothrura reichenovi*[2] and *S. buryi*,[3] all of which will probably prove to be sub-

[1] Ibis, 1915, p. 61.

[2] *Corethrura reichenovi* Sharpe, Cat. Birds Brit. Mus., Vol. 23, 1894, p. 121 ("Cameroons, W. Africa").

[3] *Sarothrura buryi* Ogilvie-Grant, Bull. Brit. Ornith. Club, Vol. 21, No. 143, 1908, p. 93 ("Dubar, Wagga Mountains, Somaliland").

species of *S. elegans.*[1] It differs from *elegans* and *buryi* in its darker coloration and heavier markings, especially as to the under parts, and, in this regard, corresponds more closely to *reichenovi.*

Description of type (and only specimen).—General color of upper parts army brown; back, rump, scapulars, and wing-coverts numerously spotted with buckthorn brown, each spot bordered with blackish above and below; bastard-wing and primary-coverts slaty brown, with small ocherous spots on the outer edge of the outer webs; quills slaty brown; upper tail-coverts and tail cinnamon-brown heavily cross-banded with black; head army brown, finely spotted with buckthorn brown and narrowly cross-banded with blackish; sides of head, including eye and lores, ochraceous-buff finely dotted with brown; ear-coverts without a dark line along the upper margin (in which respect it differs from *elegans*); chin and throat soiled white, thickly cross-banded with brownish black; chest sayal brown, spotted with bister; abdomen soiled white heavily cross-banded with blackish, the blackish bands being broader than the whitish interspaces; thighs and crissum sayal brown, spotted and obscurely cross-banded with sepia and dirty white, but with the under tail-coverts redder and broadly barred across with blackish sepia; axillars brownish-black, banded and tipped with white; under wing-coverts hair brown edged with white.

Measurements of type (adult female; measurements taken from dry skin).—Length of skin, 155; wing, 92; tail, 42; culmen (chord), 15; tarsus, 27; middle toe and claw, 32.

Remarks.—The type-specimen was taken in a "Cyclone" mouse-trap, set in a dense forest of bamboo, by J. Alden Loring, a member of the Smithsonian African Expedition, in whose honor the species is named. The following measurements and notes on the colors of the soft parts were taken by the author from the fresh specimen: Length, 188; alar expanse, 300; wing, 93; tail, 48; culmen (chord), 15; tarsus, 30; middle toe and claw, 32. Irides brown; bill purplish gray, flesh color on basal half of mandible; legs, feet, and claws uniform purplish gray.

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[1] *Gallinula elegans* A. Smith, Ill. Zool. S. Afr., Aves, 1839, pl. 22 (South Africa).

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THE SENSE ORGANS ON THE MOUTH-PARTS OF THE HONEY BEE

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CONTENTS

INTRODUCTION AND METHODS

Little experimental work has ever been performed to determine whether insects have a true gustatory sense, although the sense organs on the mouth-parts of various insects have been studied considerably. At least three different kinds of sense organs on the mouth-parts have

been called organs of taste, but no one has ever attempted to prove experimentally the function of these organs. Judging from the fact that insects prefer some foods to others and that certain insects often refuse poisoned foods, it is generally believed that insects can taste, regardless of whether or not they have gustatory organs.

At this place it is desirable to define the human senses of smell and taste, so that we may use the definitions as a basis for interpreting the responses to the same or similar stimuli in the honey bee. The sense of smell is called forth by substances in a gaseous or vaporous condition, although gases dissolved in the liquids of the mouth may give rise to actual tastes. The sense of taste is brought about by substances either in solution when introduced into the mouth, or dissolved by the liquids in the mouth. Parker and Stabler (1913), after experimenting upon themselves, and Professor Parker upon other vertebrates, say:

> We therefore definitely abandon the idea that taste and smell differ on the basis of the physical condition of the stimulus, a state of solution for taste, a gaseous or vaporous condition for smell, and maintain that both senses are stimulated by solutions, though in smell, at least for air-inhabiting vertebrates, the solvent is of a very special kind. . . . . In air-inhabiting vertebrates the olfactory solvent is a slimy fluid of organic origin and not easily imitated.

From the preceding definitions it is evident that the senses of smell and taste in vertebrates cannot be sharply separated, and the present paper will show that these two senses in the honey bee cannot be separated at all. In the honey bee it will be shown that the sense of taste is only one phase of the olfactory sense. We have not the slightest conception as to how odor and taste stimuli in any animal act upon nerve endings to produce the various sensations of smell and taste; and as shown in the following pages, when bees are fed foods which contain undesirable substances emitting extremely weak odors, they refuse to eat the foods after "tasting" them. In view of the two preceding facts we may call this perception an olfactory-gustatory sense, although the writer will endeavor to show that the gustatory sense plays no part in these responses.

In the investigation herein recorded, two objects which throw considerable light on whether or not bees have a true gustatory sense have been kept in view: (1) To determine whether bees have likes and dislikes in regard to foods, and (2) to make a careful study of the morphology of all the sense organs on the mouth-parts of the honey bee.

To obtain material for the study of the disposition of the sense organs on the mouth-parts, adult specimens were used. In regard to preparing the specimens with caustic potash and to bleaching them with chlorine gas, the reader is referred to the writer's work on Hymenoptera (1914b, p. 295).

To obtain material for the study of the internal anatomy of the sense organs herein discussed, worker pupæ 17 to 21 days old (counting from the time the eggs were laid) were mostly used, but a few adult worker bees were also employed. In regard to fixing this material in Carnoy's fluid and to embedding it in celloidin and paraffin, the reader is referred to the writer's paper on Coleoptera (1915, p. 409). The sections were cut from five to ten microns in thickness, and were stained with iron hematoxylin and eosin, safranin and gentian violet, and with Ehrlich's hematoxylin and eosin.

All the drawings were made by the writer and all are original except the internal anatomy of the mentum (*Mt*) in figure 10, which was copied from Snodgrass (1910). They were made at the base of the microscope with the aid of a camera lucida.

EXPERIMENTS TO DETERMINE WHETHER BEES HAVE LIKES AND DISLIKES IN REGARD TO FOODS

The writer (1914a) made a thorough study of the morphology and physiology of the olfactory pores found on the wings, legs, and sting of the honey bee. At that time the same organs were seen on the mouth-parts, but they were left for future study. Since the olfactory pores are so widely distributed, it is impossible to prevent all of them from functioning either by eliminating them by operations or by covering them with a substance, because the more an insect is mutilated, the more abnormal its behavior becomes. This is particularly true when the mouth-parts are mutilated. When the appendages are covered with liquid glue, vaseline, etc., bees do not eat until the substance is removed. When certain mouth-appendages are removed, bees are not entirely normal and their eating is more or less affected.

Since it is impossible to eliminate the olfactory sense while determining whether bees have a true gustatory sense, and as the various sense organs on the mouth-parts cannot be mutilated without causing considerable abnormality in the behavior of the bees while eating, it was decided to ascertain if bees have likes and dislikes in regard to foods and to make a careful study of the morphology of all the sense organs on the mouth-appendages in order to be able to judge whether or not bees have a true sense of taste.

1. Preliminary Experiments in Feeding Bees Foods Containing Various Substances

To determine the behavior of bees toward foods containing various substances under conditions which permitted of their close observation, triangular experimental cases were employed. These were made of three narrow wooden strips, two of which were ten and the third six inches long, each strip being an inch wide. Wire screen served as bottoms and tops for the cases whose apices and bases rested on supports above a table near a window.

Since cane-sugar candy is most conveniently fed to bees in experimental cases, a quantity of this food was made by thoroughly kneading a good quality of confectioner's sugar with a small amount of honey. For convenience in handling it while feeding the bees, a small lump of five grams, placed upon a small piece of cardboard, was put into each case.

Sometimes it was necessary to feed the bees honey. This food was poured into small tin feeders, each one being two and a quarter inches long, one inch wide, and one-fourth inch deep. To prevent the bees from wasting the honey, fine parallel pieces of wire, one-eighth inch apart, were stretched lengthwise over the tops of the feeders.

One drop of oil of peppermint was thoroughly mixed with 25 grams of cane-sugar candy. This mixture was then divided into five equal parts. One hundred milligrams of quinine sulphate were also thoroughly mixed with 25 grams of cane-sugar candy, and the mixture was then divided into five equal parts.

Twenty worker bees from the alighting-boards of various hives were introduced into each of five of the experimental cases, and they were immediately fed the two foods just described and an equal amount of pure cane-sugar candy. The order of placing the foods into the cases was rotated so that case No. 1 received the pure cane-sugar candy first, the candy containing oil of peppermint second and the candy containing quinine third. Case No. 2 received the candy containing oil of peppermint first, the candy containing quinine second and the pure cane-sugar candy third. Case No. 3 received the candy containing the quinine first, the pure cane-sugar candy second, and the candy containing the oil of peppermint third. Cases Nos. 4 and 5 were treated similarly. The order of arrangement of the candies in the cases was also rotated so that no two cases contained the candies in the same arrangement.

When the pure cane-sugar candy was fed first, the bees covered it and ate greedily for several moments. When the candy containing

oil of peppermint was fed first, several bees ate greedily for only a few seconds, and when pure cane-sugar candy was given to them only occasionally was a bee observed eating the candy containing oil of peppermint. When the candy containing quinine was fed first, many of the bees ate greedily until the pure cane-sugar candy was given to them; then they soon deserted the former for the latter. It was soon observed that after eating 10 minutes, the bees were able to select the candy they liked best; therefore the first count was made 10 minutes after giving them the first food and thereafter every 30 minutes. In these experiments, as in nearly all the others performed, 15 or more counts were recorded, but since some of the substances fed cause a greater mortality than others, and in order to obtain a total average as nearly uniform as possible, of the bees eating at any one count, only the first five counts have been considered. To ascertain if the direction of the light was a factor in helping to select the food, the cases were often reversed end for end. After recording the number of bees eating, they were often driven from a certain food by blowing upon them, but they invariably soon returned to the same food. As a general rule for all the experiments performed, the longer the bees were confined in the cases, the smaller was the number observed eating at any given time. Neither the direction of the light nor the arrangement of the food in the cases is a factor in helping to select the foods they like best.

The preceding set of experiments was repeated twice. As an average for the 300 bees for five counts, 35.8 per cent of the bees were seen eating pure cane-sugar candy, none eating candy containing oil of peppermint, and 2.3 per cent were observed eating candy containing quinine, making a total average of 38.1 per cent eating at any one count. Twelve bees in case No. 4 of the first set of experiments began to die when the fifth count was recorded. They had freely eaten the candy containing quinine.

Two days later three grams of chinquapin (*Castanea pumila*) honey were poured into each of five feeders. This food was then given to the bees used in the third set of experiments just described. During the first 15 minutes after introducing the honey, only seven bees ate a little of it. After that they walked over the feeders, but never offered to eat the honey again. This honey has a strong, characteristic, bitter odor. As an average for the 100 bees for five counts, 15 minutes after introducing the honey 24.8 per cent were seen eating pure cane-sugar candy at any one count, but none was noticed eating

the candies containing oil of peppermint and quinine or the chinquapin honey.

The following day honey containing oil of peppermint was substituted for the chinquapin honey. This was had by mixing one drop of the oil of peppermint in 25 cubic centimeters of honey, and the mixture was then divided into five equal parts. It emitted only a faint odor of peppermint, but when eaten by the writer the peppermint attribute was quite pronounced. It no longer tasted like honey. During the first five minutes only a few bees ate a little of it, and after that none offered to eat it. As an average for the 100 bees for five counts, 26.6 per cent were observed eating pure cane-sugar candy at any one count, but none was seen eating the candies and the honey containing oil of peppermint and quinine. Later the pure cane-sugar candy in case No. 1 became exhausted, and instead of the bees selecting either the candy or the honey containing oil of peppermint, they chose the candy containing quinine. For two hours they ate it as freely as they previously had eaten the pure cane-sugar candy, but after the third hour they ceased to eat it. By this time a few were dead and several were sick.

One drop of cider vinegar was mixed with 25 grams of cane-sugar candy and one drop of carbolic acid was mixed with an equal amount of cane-sugar candy. Each one of these mixtures was then divided into five equal parts. Fresh bees were introduced into the cases and were fed pure cane-sugar candy and the mixtures just described. As an average for the 100 bees for five counts, 17.4 per cent were observed eating pure cane-sugar candy, 28.8 per cent eating candy containing vinegar, and 1.4 per cent were seen eating candy containing carbolic acid, making a total average of 47.6 per cent eating at any one count. The vinegar seemed to have brought about a chemical change in the candy and probably inverted the cane sugar. After the fifth count the bees ate this candy more freely than before.

Two days later the candy containing vinegar was removed and candy containing alum was placed in its exact position. The latter candy was composed of one-half powdered alum, and the other half of powdered sugar and honey. At first the bees ran over it, and thereafter only occasionally ate a little of it. As an average for the 100 bees for five counts, 19.2 per cent were seen eating pure cane-sugar candy, 3.8 per cent eating candy containing carbolic acid, and 3.4 per cent were seen eating candy containing alum, making a total average of 26.4 per cent eating at any one count. The candy containing carbolic acid at this time emitted only a faint odor.

The following day mannose (a monosaccharide or simple sugar) candy was given to the bees used in the preceding experiments. This candy was made by kneading pure mannose (crystallized and washed twice) and honey. For a few moments the bees in two cases seemed to like the mannose candy equally as well as the cane-sugar candy, although after a short time they became sick and later several died. As an average for the 100 bees for five counts, 24.2 per cent were observed eating pure cane-sugar candy, 0.2 per cent eating candy containing carbolic acid, none eating candy containing alum and 3.6 per cent were seen eating mannose candy, making a total average of 28.1 per cent eating at any one count.

Fifteen grams of common salt (NaCl) were kneaded in honey. This mixture was then divided into five equal parts. It and chinquapin honey were fed to fresh bees. During the first 15 minutes the bees ate the salt containing honey rather freely, but seldom touched the chinquapin honey and after that seldom ate any of either food. Forty-five minutes after introducing the food, several bees in each case began to die. As an average for the 100 bees for five counts, 2.2 per cent were seen eating chinquapin honey and 2 per cent eating salt containing honey, making a total average of 4.2 per cent eating at any one count.

The following is a tabulated summary of the preceding results obtained by feeding bees foods containing various substances. The figures in the third to tenth columns represent the average per cent or number of bees eating a particular food at any one count.

TABLE I

Preliminary Experiments in Feeding Bees Foods Containing Various Substances

Number of bees used	Number of counts	Average per cent of bees eating foods containing various substances										Total average per cent of bees feeding at any one count
		Pure cane-sugar candy	Cane-sugar candy containing oil of peppermint	Cane-sugar candy containing quinine	Chinquapin honey	Honey containing oil of peppermint	Cane-sugar candy containing cider vinegar	Cane-sugar candy containing carbolic acid	Cane-sugar candy containing alum	Mannose candy	Salt containing honey	
300	5	35.8	0.0	2.3	....	....	....	....	....	....	....	38.1
100	5	24.8	0.0	0.0	0.0	....	....	....	....	....	....	24.8
100	5	26.6	0.0	0.0	....	0.0	....	....	....	....	....	26.6
100	5	17.4	....	....	....	....	28.8	1.4	....	....	....	47.6
100	5	19.2	....	....	....	....	....	3.8	3.4	....	....	26.4
100	5	24.2	....	....	....	....	....	0.2	0.0	3.6	....	28.0
100	5	....	....	....	2.2	....	....	....	....	....	2.0	4.2

The preceding preliminary experiments clearly show the following: (1) In regard to foods bees have likes and dislikes; (2) before showing preferences between foods bees always eat more or less of them first, unless the foods contain strong repellents; (3) the longer the bees are confined in the experimental cases the less they eat, and (4) some of the substances fed are injurious to them. For the last two reasons only the first five counts are sufficiently reliable for determining the total average per cent of bees eating at any one count. These experiments indicate that bees may have a sense of taste, because neither the direction of the light nor the arrangement of the food in the cases helps in selecting the food they like best, and the olfactory sense may not be the sole factor in selecting foods, for bees must usually eat more or less of them before being able to show preferences between them. It is probable that bees cease eating some foods because their alimentary tracts may be affected, and for this reason alone they may reject the particular food that does not agree with them.

The preceding results suggest five classes of foods to be used in the following experiments. Foods containing strong repellents may be employed to determine the importance of the olfactory sense in causing bees to avoid such substances, and foods containing sweet, bitter, sour, and salty substances may be used to ascertain if bees show preferences between foods having the four attributes of human taste.

2. Experiments in Feeding Bees Foods Containing Repellents

Pure cane-sugar and candy containing oil of peppermint (described above, page 4) were fed to fresh bees in the cases as described in the preceding pages. After waiting 10 minutes the first count was recorded, and thereafter every 30 minutes. As an average for the 100 bees for five counts, 35.4 per cent were seen eating the pure cane-sugar candy at any one count, while they never touched the candy containing oil of peppermint.

The preceding was repeated by feeding candy containing carbolic acid (described on p. 6) and pure cane-sugar candy to fresh bees. As an average for the 100 bees for five counts, 41.4 per cent were seen eating pure cane-sugar at any one count, while none touched the candy containing carbolic acid.

The preceding was repeated by feeding pure honey and honey containing whiskey to fresh bees. Four grams of pure honey were

poured into each of five feeders, and the same amount containing three drops of whiskey was likewise poured into each of five other feeders. The odor of whiskey from the latter food was not pronounced to the writer, but the taste of whiskey was quite pronounced. When these foods were introduced into the cases the bees ate one as freely as the other. Five minutes after feeding them the first count was taken and thereafter every five minutes. Since it takes bees confined in these cases only 10 to 15 minutes to fill their honey stomachs with liquid foods, only two counts were taken. As an average for the 100 bees for two counts, 30 per cent were seen eating pure honey and 22 per cent eating honey containing whiskey, making 52 per cent eating at any one count.

A mixture of 25 cubic centimeters of honey and two drops of carbolic acid was divided into five equal parts, each part being fed to 20 fresh bees in the usual manner. For the first 15 minutes after introducing the food, the bees avoided it, but later a few ate it to a limited degree. As an average for the 100 bees for five counts, 3 per cent were seen eating it at any one count. Nine days later this honey did not emit such a strong carbolic-acid odor. It was again fed to bees. Only two counts were taken. As an average for the 100 bees, 27.5 per cent were seen eating at any one count.

The preceding was repeated by feeding honey containing oil of peppermint (described on p. 4) to fresh bees. As long as the mixture emitted a strong odor of peppermint the bees avoided it, but nine days after preparing the mixture the bees ate it rather freely. As an average for the 100 bees, 27.5 per cent were seen eating it at any one count.

Twenty-five cubic centimeters of honey were mixed with two drops of each of the following: formic acid, sulphuric acid, xylol, formaldehyde, kerosene, and lime-sulphur. The bees usually avoided these mixtures, but occasionally one or two offered to eat a little of the food. The first count was recorded 30 minutes after introducing the food and thereafter every hour. As an average for the 100 bees in each set of experiments for five counts, the following numbers represent the bees seen eating at any one count: Formic acid—7.4 per cent, sulphuric acid—4.2 per cent, xylol—5.2 per cent, formaldehyde—3.2 per cent, kerosene—1.6 per cent, and lime-sulphur—1.2 per cent.

The following is a tabulated summary of the preceding results obtained by feeding bees foods containing repellents. The figures

in the third to fourteenth columns represent the average per cent or number of bees eating a particular food at any one count.

TABLE II

Experiments in Feeding Bees Foods Containing Repellents

Number of bees used	Number of counts	Pure cane-sugar candy	Pure honey	Average per cent of bees eating pure foods and foods containing repellents										Total average per cent of bees feeding at at any one count
				Cane-sugar candy containing carbolic acid	Cane-sugar candy containing oil of peppermint	Honey containing whiskey	Honey containing formic acid	Honey containing xylol	Honey containing sulphuric acid	Honey containing formaldehyde	Honey containing carbolic acid	Honey containing kerosene	Honey containing lime-sulphur	
100	5	35.4	......	......	0.0	......	...	...	...	...	...	......	......	35.4
100	5	41.4	......	0.0	......	......	...	...	...	...	...	......	......	41.4
100	2	......	30.0	......	......	22.0	...	...	...	...	...	......	......	52.0
100	5	......	......	......	......	......	7.4	...	...	...	...	......	......	......
100	5	......	......	......	......	......	...	5.2	...	...	...	......	......	......
100	5	......	......	......	......	......	...	...	4.2	...	...	......	......	......
100	5	......	......	......	......	......	...	...	...	3.2	...	......	......	......
100	5	......	......	......	......	......	...	...	...	...	3.0	......	......	......
100	5	......	......	......	......	......	...	...	...	...	...	1.6	......	......
100	5	......	......	......	......	......	...	...	...	...	...	......	1.2	......

The preceding results clearly show that when bees are given preferences between pure foods and foods containing strong repellents they freely eat the former and refuse the latter, and when they are fed foods containing repellents without having a preference for pure foods, they eat sparingly. Judging from these experiments we are certainly safe in saying that the bees avoided the foods containing repellents on account of the odors emitted from these substances.

3. Experiments in Feeding Bees Sweet Foods

To ascertain if bees show preferences between sweet foods, the following candies were made by using basswood honey with chemically pure potato starch, dextrine and the following sugars: saccharine, mannose, levulose, dextrose, raffinose, lactose and maltose. An equally small amount of honey was kneaded with 15 grams of each of the above nine substances, except that only eight grams of saccharine were used. Each lump of candy was then divided into five equal parts. In the order of the sweetest to the writer, the eight sugars stand as given above. Saccharine, varying from 300 to 500 times as sweet as cane sugar, has a disagreeable sweet-sickening taste.

Mannose, which appears to be almost as sweet as saccharine, has a disagreeable, bitter-sweet taste. Each one of these sugars has its own faint, characteristic odor, but the predominating odor emitted from the candy made of each is that of honey. To the writer the starch candy gave off only one faint odor, that of honey. Dextrine is light yellow and emits a stronger odor than does any one of the sugars.

Twenty fresh bees were introduced into each of five cases. When the preceding nine candies were put into the cases, the bees wandered about considerably and ate a little of each candy, but ate the mannose and levulose most greedily. A short time after eating the mannose, many of the bees began to die. Thirty minutes after feeding the bees, the first count was taken, and thereafter every half hour. The four counts recorded showed that only one bee was seen eating mannose, four eating levulose and none eating any of the other candies. This small number is certainly due to most of the bees soon becoming sick and some dying.

The preceding experiments were repeated by feeding cane-sugar (saccharose), saccharine, mannose and levulose candies to fresh bees. As usual the bees wandered about considerably and ate a little of each candy except the saccharine. An hour later those that had eaten the mannose became sick and ate no more that day, but the next morning most of them had recovered and a few were seen eating a little. As a total for the 100 bees for 17 counts, 10.7 per cent were seen eating cane-sugar, 6 per cent eating levulose, 1 per cent eating saccharine and none eating mannose candy.

To ascertain if bees could be forced to eat saccharine, fresh bees and a lump of the saccharine candy were put into each of the five cases. The bees perched upon and ran over the candy as if it were a piece of wood. It neither repelled nor attracted them, and during an entire hour only five bees licked the candy for a few seconds. The starch candy was next tried alone. During the first ten minutes several bees ate it rather freely, but after that for an hour only occasionally did a bee eat a little of it.

Cane-sugar, dextrose, dextrine and raffinose candies were put into each case, and fresh bees were employed as usual. As an average for the 100 bees for five counts, 41.2 per cent were seen eating cane-sugar, 2.6 per cent eating dextrose, none eating dextrine and 0.2 per cent eating raffinose candy, making a total average of 44 per cent eating at any one count.

Levulose, dextrose and raffinose candies were next used. As an average for the 100 bees for five counts, 20 per cent were seen eating

levulose, none eating dextrose and 1.8 per cent eating raffinose candy, making a total average of 21.8 per cent eating at any one count.

Dextrose, raffinose and dextrine candies were used in the same way. As an average for the 100 bees for five counts, 21 per cent were seen eating raffinose, 12 per cent eating dextrose and 6.8 per cent eating dextrine candy, making a total average of 39.8 per cent eating at any one count.

Dextrine, lactose and maltose candies were used in the same way. As an average for the 100 bees for five counts, 42 per cent were observed eating maltose candy at any one count, but none was seen eating lactose or dextrine candy.

The preferences shown between these candies may have been partially due to the amount of water in them. No two of these candies absorbed the same amount of water vapor from the air, but during the first day the water in any of them was not noticeable, although after that it was quite noticeable. Levulose absorbed the most water vapor and saccharine the least.

Dextrose, raffinose and maltose candies were next used. As an average for the 100 bees for five counts, 16 per cent were seen eating maltose, 12 per cent eating raffinose and 7 per cent eating dextrose candy, making a total average of 35 per cent eating at any one count.

To ascertain if bees show preferences between honeys, an equal amount of light-colored honey and dark-colored honey was poured into each of five feeders. Perhaps most of the light-colored honey came from basswood trees, while the source of the dark-colored honey was unknown. The latter honey was taken in the crystallized form from old combs and was then melted. The odors and tastes of these two honeys were quite different. Fresh bees from the alighting-boards were introduced into the cases, and during the first five minutes after giving them the two honeys, they ate each one greedily. By the time they had eaten five minutes, most of them had selected the honey they liked the better. At this stage the ones eating were counted, and five minutes later were counted again. After this few were seen eating, because nearly all of them by this time had filled their honey stomachs. This set of experiments was repeated twice. As an average for the 300 bees for two counts, 24.3 per cent were seen eating the light-colored honey and 18.8 per cent the dark-colored honey, making a total average of 43.1 per cent eating at any one count.

Fresh bees were placed in the cases, and they were fed light-colored honey and sugar syrup (half sugar and half water) in the same manner as just described. As an average for the 100 bees for

two counts, 37 per cent were seen eating the honey and 4 per cent the syrup, making a total average of 41 per cent eating at any one count.

In the same manner light-colored honey and pollen mixed thoroughly with light-colored honey (1 part pollen to 4 parts honey) were given to fresh bees. As an average for the 100 bees for three counts, 26.3 per cent were seen eating the light-colored honey and 16.3 per cent the honey mixed with pollen, making a total average of 42.6 per cent eating at any one time.

In the same way light-colored honey, and sugar mixed with light-colored honey (half and half) were fed to bees. As an average for the 100 bees for five counts, 30.4 per cent were seen eating the honey and 11 per cent the mixture of sugar and honey, making a total average of 41.4 per cent eating at any one count. Since one of these foods was a thick paste, five counts were recorded before the bees ceased eating, while in the experiments just preceding only three counts were necessary, because the mixture of pollen and honey made a thin paste.

The following is a tabulated summary of the preceding results obtained by feeding bees sweet foods. The figures in the third to fourteenth columns represent the average per cent or number of bees eating a particular food at any one time.

TABLE III

Experiments in Feeding Bees Sweet Foods

Number of bees used	Number of counts	Average per cent of bees eating candies							Average per cent of bees eating liquid foods					Total average per cent of bees feeding at any one count
		Cane-sugar candy	Levulose candy	Maltose candy	Raffinose candy	Dextrose candy	Lactose candy	Dextrine candy	Light-colored honey	Dark-colored honey	Sugar syrup (1 pt. sugar to 1 pt. water	Light-colored honey and pollen (4 pt. honey to 1 pt. pollen)	Light-colored honey and sugar (1 pt. honey to 1 pt. sugar)	
100	5	41.2	....	....	0.2	2.6	...	0.0	......	....	....	......	......	44.0
100	5	....	20.0	....	1.8	0.0	...	...	......	....	....	......	......	21.8
100	5	....	....	....	21.0	12.0	...	6.8	......	....	....	......	......	39.8
100	5	....	....	42.0	....	....	0.0	0.0	......	....	....	......	......	42.0
100	5	....	....	16.0	12.0	7.0	...	...	......	....	....	......	......	35.0
100	2	....	....	....	....	....	...	...	24.3	18.8	....	......	......	43.1
100	2	....	....	....	....	....	...	...	37.0	....	4.0	......	......	41.0
100	3	....	....	....	....	....	...	...	26.3	....	....	16.3	......	42.6
100	5	....	....	....	....	....	...	...	30.4	....	....	......	11.0	41.4

It is evident from the above table that bees show preferences between sweet foods.

4. Experiments in Feeding Bees Foods Containing Bitter Substances

Two lots of 25 grams of cane-sugar candy each were thoroughly mixed, one with 500 milligrams of finely pulverized quinine sulphate and the other with a like quantity of strychnine sulphate. Each mixture was then divided into five equal parts. To the writer the odor from each mixture was exactly like that from pure cane-sugar candy, although the human nose is able to detect a faint odor emitted from a large quantity of either quinine or strychnine. Strychnine is regarded as the bitterest of all substances. To the writer both of these mixtures were extremely bitter. Equal amounts of pure cane-sugar candy and of these other two foods were fed to fresh bees in the usual manner. Five minutes after introducing the foods, the first count was taken and thereafter every 15 minutes. As an average for the 100 bees for five counts, 47.4 per cent were observed eating pure cane-sugar candy, 5.8 per cent eating candy containing quinine, and 4 per cent eating candy containing strychnine, making a total average of 57.8 per cent eating at any one count.

These experiments were repeated by feeding fresh bees only the candies containing quinine and strychnine. As an average for the 100 bees for five counts, 39.4 per cent were seen eating candy containing quinine and 4 per cent eating candy containing strychnine, making a total average of 43.4 per cent eating at any one count. An hour after introducing the foods, the bees began to die.

Twenty-five grams of cane-sugar candy were mixed with 500 milligrams of liquid picric acid, and then the mixture was divided into five equal parts. This food was almost as bitter as quinine and emitted a faint odor, different from that of pure cane-sugar candy. The preceding experiments were repeated by feeding fresh bees this mixture, candy containing quinine and pure cane-sugar candy. As an average for the 100 bees for five counts, 19.2 per cent were seen eating pure cane-sugar candy, 34.4 per cent eating candy containing picric acid and 2.2 per cent eating candy containing quinine, making a total average of 55.8 per cent eating at any one count.

The preceding was repeated by using the same amount of powdered picric acid instead of the liquid picric acid and by discarding the candy containing quinine. As an average for the 100 bees for five counts, 45 per cent were observed eating pure cane-sugar candy and 1 per cent eating candy containing picric acid, making a total average of 46 per cent eating at any one count.

The experiments just described were repeated by making a candy of powdered picric acid and honey. As an average for the 100 bees for five counts, 45 per cent were seen eating the pure cane-sugar candy at any one count, but none ate the candy made of picric acid and honey. Judging from the three sets of experiments in which picric acid was used, it seems that this acid in the liquid form effects a chemical change in cane sugar, thereby causing bees to prefer candy mixed with it to pure cane-sugar candy.

Chinquapin honey, which has a bitter taste, was next fed to bees as described on page 5. As an average for the 100 bees for seven counts, only 3.4 per cent were seen eating at any one count.

The following is a tabulated summary of the preceding results obtained by feeding bees foods containing bitter substances. The figures in the third to ninth columns represent the average per cent or number of bees eating a particular food at any one count.

TABLE IV

Experiments in Feeding Bees Foods Containing Bitter Substances

Number of bees used	Number of counts	Pure cane-sugar candy	Average per cent of bees eating foods containing bitter substances						Total average per cent of bees feeding at any one count
			Cane-sugar candy containing quinine	Cane-sugar candy containing strychnine	Cane-sugar candy containing liquid picric acid.	Cane-sugar containing powdered picric acid	Candy made of powdered picric acid and honey	Chinquapin honey	
100	5	47.4	5.8	4.6	....	....	......	......	57.8
100	5	......	39.4	4.0	....	....	......	......	43.4
100	5	19.2	2.2	....	34.4	....	......	......	55.8
100	5	45.0	......	....	....	1.0	......	......	46.0
100	5	45.0	......	....	....	....	0.0	......	45.0
100	7	......	......	....	....	....	......	3.4	....

Judging from the above table, it is plain that bees show preferences between foods containing bitter substances.

5. Experiments in Feeding Bees Foods Containing Sour Substances.

Twenty grams of honey were thoroughly mixed with 45 drops of lemon juice. The lemon juice made the honey considerably thinner and gave it a slightly different odor and a slightly sour taste. This mixture and an equal amount of pure honey, after being divided into five equal parts, were fed to fresh bees in the usual manner. As an

average for the 100 bees for two counts, 26.5 per cent were observed eating pure honey and 17 per cent eating honey containing lemon juice, making a total of 43.5 per cent eating at any one count.

The preceding was repeated by using three drops of acetic acid (99.5 per cent) in each feeder containing four grams of honey. The acid made the honey quite sour and changed its odor slightly. As an average for the 100 bees for two counts, 28 per cent were seen eating pure honey and 5.5 per cent eating honey containing acetic acid, making 33.5 per cent eating at any one count.

Hydrochloric acid (37 per cent) was used in the same manner. It slightly changed the odor of the honey and gave it a sharp, sour taste. As an average for the 100 bees for two counts, 50 per cent were observed eating pure honey at each count, but none ate the honey containing acid.

Sulphuric acid (95 per cent) was next used in the same manner. This acid gave the honey a less sharp, sour taste than did hydrochloric acid. As an average for the 100 bees for two counts, 28.5 per cent were seen eating pure honey at each count, while none ate the honey containing acid.

Nitric acid (68 per cent) was employed in the same way. This acid gave the honey a sour taste, although not sharp. As an average for the 100 bees for two counts, 33.5 per cent were observed eating pure honey at each count, while none ate the honey containing acid.

The following is a tabulated summary of the preceding results obtained by feeding bees foods containing sour substances. The figures in the third to eighth columns represent the average per cent or number of bees eating a particular food at any one count.

TABLE V

Experiments in Feeding Bees Foods Containing Sour Substances

Number of bees used	Number of counts	Average per cent of bees eating foods containing sour substances						Total average per cent of bees feeding at any one count
		Pure honey	Honey containing lemon juice	Honey containing acetic acid	Honey containing hydrochloric acid	Honey containing sulphuric acid	Honey containing nitric acid	
100	2	26.5	17.0	....	....	....	....	43.5
100	2	28.0	....	5.5	....	....	....	33.5
100	2	50.0	....	....	0.0	....	....	50.0
100	2	28.5	....	....	....	0.0	....	28.5
100	2	33.5	....	....	....	....	0.0	33.5

Judging from the above table, it is seen that bees prefer pure honey to honeys containing sour substances.

6. Experiments in Feeding Bees Foods Containing Sodium Salts

Five lots, each containing 15 grams of cane-sugar candy, were each thoroughly mixed respectively with 500 milligrams of the following finely pulverized and chemically pure salts: sodium chloride (common salt), sodium sulphite, sodium nitrate, sodium carbonate and sodium fluoride. Each one of these mixtures was then divided into five equal parts. Each of the salts used has a faint odor and no two have odors alike, and the odor of each mixture was slightly different from that of pure candy. The taste of the mixture containing sodium chloride was slightly salty and the tastes of the other mixtures were more or less different from that of pure candy; no two were alike and none was exactly salty. Sodium fluoride has a sharp, astringent taste and seems to burn the mucous membrane. Some of the mixtures absorbed more water vapor from the air than others and some changed slightly in color. All five mixtures and pure cane-sugar candy were fed to fresh bees in the usual manner. At first the bees ate a little of each candy, and before having time to select the ones they liked best, many bees became sick and soon began to die.

Pure cane-sugar candy and the candy containing sodium chloride were tried alone. Since all these salts were more or less injurious to bees, the first count was made five minutes after introducing the food and thereafter every 15 minutes. As an average for the 100 bees for five counts, 39.6 per cent were seen eating pure cane-sugar candy and 5.8 per cent eating the candy containing sodium chloride, making a total average of 45.4 per cent eating at any one count.

The candies containing sodium carbonate and sodium sulphite were tried alone. As an average for the 100 bees for five counts, 9 per cent were observed eating the latter mixture, but only 0.6 per cent eating the former mixture, making a total average of 9.6 per cent eating at any one count. A half hour after introducing the food, many bees were sick and a half hour still later several were dead.

The mixture containing sodium nitrate and sodium fluoride were next tried alone. As an average for the 100 bees for five counts, 2.2 per cent were seen eating the latter mixture and 9.6 per cent eating the former mixture, making a total average of 11.8 per cent eating at any one count. A half hour after feeding the bees, many became sick and soon began to die.

Pure cane-sugar candy and the mixture containing sodium carbonate were fed alone. As an average for the 100 bees for five counts, 56.6 per cent were observed eating pure cane-sugar candy at any one count, while none ate the mixture containing sodium carbonate.

Pure cane-sugar candy and the mixture containing sodium sulphite were also fed alone. As an average for the 100 bees for five counts, 52.2 per cent were seen eating pure cane-sugar candy and 3.2 per cent eating the mixture containing sodium sulphite, making a total average of 55.4 per cent eating at any one count. An hour after introducing the food, a few bees became sick.

Pure cane-sugar candy and the mixture containing sodium nitrate were likewise fed alone. As an average for the 100 bees for five counts, 45.6 per cent were seen eating pure cane-sugar candy and 3.8 per cent eating the mixture containing sodium nitrate, making a total average of 49.4 per cent eating at any one count.

Pure cane-sugar candy and the mixture containing sodium fluoride were fed last. As an average for the 100 bees for five counts, 32.2 per cent were observed eating pure cane-sugar candy and only 0.4 per cent eating the mixture containing sodium fluoride, making a total average of 32.6 per cent eating at any one count. A half hour after introducing the food, several bees became sick.

The following is a tabulated summary of the preceding results obtained by feeding bees foods containing sodium salts. The figures in the third to eighth columns represent the average per cent or number of bees eating a particular food at any one count.

TABLE VI

Experiments in Feeding Bees Foods Containing Sodium Salts

Number of bees used	Number of counts	Pure cane-sugar candy	Average per cent of bees eating foods containing sodium salts					Total average per cent of bees feeding at any one count
			Cane-sugar candy containing sodium chloride	Cane-sugar candy containing sodium nitrate	Cane-sugar candy containing sodium sulphite	Cane-sugar candy containing sodium fluoride	Cane-sugar candy containing, sodium carbonate	
100	5	39.6	5.8	....	....	....	....	45.4
100	5	45.6	....	3.8	....	....	....	49.4
100	5	52.2	....	....	3.2	....	....	55.4
100	5	32.2	....	....	....	0.4	....	32.6
100	5	56.6	....	....	....	....	0.0	56.6
100	5	......	....	....	9.0	....	0.6	9.6
100	5	......	....	9.6	....	2.2	....	11.8

Judging from the above table, it is seen that bees prefer pure cane-sugar candy to any one of the above foods containing sodium salts, and that they show preferences between these various mixtures.

7. Experiments in Feeding Bees Foods Containing Potassium Salts

The preceding experiments were repeated by using potassium bromide, potassium carbonate, potassium cyanide, potassium ferrocyanide, potassium iodide, and potassium nitrate. When potassium bromide, potassium ferrocyanide, and potassium nitrate were mixed

TABLE VII

Experiments in Feeding Bees Foods Containing Potassium Salts

No. of bees used	No. of counts	Pure cane-sugar candy	Average per cent of bees eating foods containing potassium salts						Total average per cent of bees feeding at any one count
			Cane-sugar candy containing potassium bromide	Cane-sugar candy containing potassium carbonate	Cane-sugar candy containing potassium cyanide	Cane-sugar candy containing potassium ferrocyanide	Cane-sugar candy containing potassium iodide	Cane-sugar candy containing potassium nitrate	
100	5	36.2	9.6	....	....	....	......	......	45.8
100	5	40.2	......	0.4	....	....	......	......	40.6
100	5	43.8	......	....	0.0	....	......	......	43.8
100	5	24.6	......	....	....	12.4	......	......	37.0
100	5	29.8	......	....	....	....	5.0	......	34.8
100	5	26.8	......	....	....	....	......	5.4	32.2
100	5	......	......	....	0.0	33.4	......	......	33.4
100	5	......	15.6	0.0	....	....	......	......	15.6
100	5	......	......	....	....	....	6.0	3.6	9.6

with pure cane-sugar candy, the mixtures emitted odors and tasted like pure cane-sugar candy as far as the writer could detect. Potassium carbonate and potassium iodide did not change the odor of the cane-sugar candy when mixed with it, but each gave the mixture a slightly bitter taste. The potassium cyanide gave the cane-sugar candy a slightly bitter taste and a comparatively strong odor like cyanogen. It changed the candy from white to a lemon-like color. Three of the other mixtures were also changed slightly in color. The six mixtures were fed, two at a time, to fresh bees, and then each one was fed with pure cane-sugar candy in the manner described for the foods containing the sodium salts. When the bees ate the mixtures containing potassium bromide, potassium carbonate, potassium iodide, and potassium nitrate, they soon became sick and thereafter

almost ceased eating. They wholly refused to eat candy containing potassium cyanide but freely ate the mixture containing potassium ferrocyanide, and this salt apparently did not affect them. A detailed account of these experiments is not necessary, because the results are similar to those when the sodium salts were used.

Table VII is a tabulated summary of the results obtained by feeding bees with foods containing potassium salts. The figures in the third to ninth columns represent the average per cent or number of bees eating a particular food at any one count.

It is evident from the above tabulated results that bees prefer pure cane-sugar candy to the mixtures containing potassium salts, and that they also show preferences between foods containing these salts.

8. Summary of Preceding Experiments

The preceding results clearly demonstrate that bees have likes and dislikes in regard to foods, and it seems that their faculty to discriminate between foods is more highly developed than ours, because they can distinguish differences between the foods fed to them better than the writer. The candies containing strychnine and quinine best illustrate this point. Equal amounts of these two bitter salts were used; but when the writer tasted the candies containing them, little or no difference in bitterness could be detected, although, judging from the number of bees that ate them when the two foods were fed alone, the bees distinguished a marked difference between them.

As a general rule, foods agreeable to us are also agreeable to bees, but there are a few marked exceptions. All foods scented with peppermint are pleasant to us, but repellent to bees. The writer does not care for candy containing potassium ferrocyanide, but bees are rather fond of it, and it does not seem harmful to them.

In regard to the repellents used, the few experiments performed do not warrant definite deductions, but the results indicate that lime-sulphur and kerosene are the strongest of the repellents used, while formic acid repels the least and carbolic acid the most among the acids. That the acids as a rule are not better repellents may possibly be explained by the fact that bees are more or less accustomed to the odors from the acids found in their foods and various secretions.

The results obtained demonstrate that bees like honey best of all foods and that they are able to distinguish marked differences between various kinds of honeys. Substitutes for honey as food for bees may be better than honey in a few instances, but these investi-

gations indicate that no substitute can be had which will be liked by bees as well as the best pure honey.

The fact that bees must first eat more or less of the foods before being able to discriminate differences between them, unless they contain repellents, indicates that bees have a true gustatory sense, providing this discrimination is not accomplished by means of the olfactory sense. Since this point cannot be determined experimentally, our only criterion is to make a thorough study of all the sense organs on and near the mouth-parts. This part of the work is given in the following pages.

MORPHOLOGY OF THE SENSE ORGANS ON THE MOUTH-PARTS OF THE HONEY BEE

In the preceding pages it is stated that bees show preferences between foods. In order that they may show preferences between the foods emitting weak odors, it is first necessary for them to eat a little of the foods. This fact indicates that bees may have a true sense of taste. If the mouth-parts possess sense organs which are anatomically fitted for receiving gustatory stimuli, we are safe in saying that bees can taste. In order to find such organs, if possible, it was necessary to make a special study of all the sense organs on and near the mouth-parts. In order to distinguish the sense organs from other structures on the mouth-parts, the internal anatomy of all the structures on the integument was first studied. This was accomplished by making many transverse and longitudinal sections through all parts of the mouth-appendages and even through the entire head. Only two general types of sense organs were found; *viz.:* innervated hairs and innervated pores.

Hairs on the honey bee are of two kinds—branched or barbed hairs and unbranched ones. As far as known the branched ones are never innervated and are never found on the mouth-appendages, but on the head near the mouth-parts and elsewhere. The unbranched hairs not only occur on the mouth-appendages but also on the other parts of the integument, although most abundantly on the mouth-parts and compound eyes. They may or may not be innervated.

All true hairs, whether branched or unbranched, arise from hair sockets (fig. 2 Q, *HrSk*) whose cavities (*SkCav*) communicate with the lumens (*L*) of the appendages and with the cavities (*HrCav*) of the hairs. The long hairlike structures (fig. 3 A, Hr^1) on the tongue or glossa may be called pseudo-hairs, because they are merely

prolongations of the chitin. They do not arise from sockets, are not hollow and do not communicate with the lumen (*L*) of the tongue. The spoon-shaped lobe, the labellum (fig. 7, *Lbl*) forming the tip of the tongue, is also covered with pseudo-hairs. These are short and thick and are branched at their tips, while those on the tongue are long and slender and are unbranched. Several minute pseudo-hairs are also present on the dorsal side of the mentum (fig. 7, *Mt*) and elsewhere on various parts of the integument.

The writer in 1914 made a study of the innervated pores (called olfactory pores) found on the wings, legs, and sting of the honey bee.

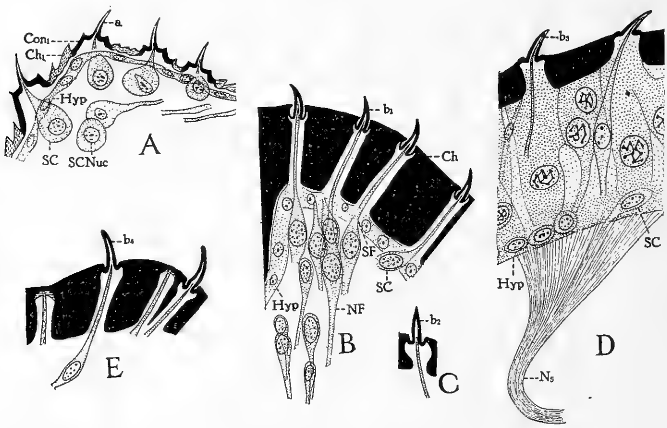

FIG. 1.—Internal anatomy of varieties *a* and *b* of spinelike, innervated hairs of worker honey bees, x 580. A, variety *a* on epipharynx (figs. 9 A and 10, *Ep*). B, C, D and E, variety *b*: b_1 from outer surface at proximal end of mandible (fig. 7, *Md*), b_2 from inner surface at distal end of mandible (fig. 8, *Md*), b_3 from pharyngeal plate (figs. 9 B and 10, *PhPl*), and b_4 from outer surface at tip of mandible (fig. 7, *Md*). C from 17-day-old pupa, B and E from 20-day-old pupæ, and A and D from 21-day-old pupæ. The nerve (N_5) in D is taken from a deeper focus than the other parts in the figure. See page 54 for explanation of abbreviations.

At that time he also saw the same pores on the mouth-parts, and since then has seen a few on each antenna near its articulation with the head.

1. Structure of the Innervated Hairs

Innervated hairs may be roughly divided into spinelike and peglike hairs, although there is no sharp dividing line between the two classes. The different varieties of these two classes vary gradually from long, slender hairs to short, stubby ones. For description the varieties may be designated alphabetically.

(a) SPINELIKE HAIRS

Variety a. In describing the spinelike hairs we shall begin with the most delicate ones and then proceed toward the largest, and we shall carefully examine the anatomy of each variety to ascertain if it is anatomically adapted for receiving odor stimuli.

In regard to the thickness of the walls, the most delicate variety is found on the epipharynx (figs. 9 A and 10, *Ep*). These are not typically true hairs, because they do not arise from hair sockets, but from small cones (fig. 1 A, Con_1) which, however, might be regarded as another type of sockets. Of all the hairs, these have the thinnest walls. The walls become gradually thinner from the bases to the tips. These hairs are so small and so light in color that they are easily overlooked. Each one arises from the summit of a small cone whose walls are thick and are dark in color, while the chitin (Ch_1) between the cones is light in color. Chitin is stained little or not at all with Ehrlich's hematoxylin. Flexible chitin is usually light in color, and when chitin is not flexible it is generally dark in color. For this reason these hairs cannot be bent at their bases but may be bent near their tips; and likewise the cones, which project slightly above the level of the surrounding chitin, are rigid, but since the surrounding chitin is flexible each cone with its hair has considerable freedom of motion.

In most cross-sections through the epipharynx showing these hairs the sense cells are grouped together so closely that each hair seems to be provided with either a multinucleated sense cell or with more than one cell, each having only one nucleus. In extremely thin sections where the sense cells are not piled upon one another, however, it is clearly seen that each hair is innervated by a single sense cell (fig. 1 A, *SC*) having only one nucleus (*SCNuc*). In the 21-day-old pupa the hypodermis (*Hyp*) is comparatively thin.

Wolff (1875) regarded these cones with their hairs as having an olfactory function, and according to their anatomy they are adapted equally as well for gustatory organs, but since chitin after once formed is dead matter and is not porous, it does not seem reasonable to think of either odoriferous particles or liquid foods being able to pass into the hairs in order that the nerves may be stimulated, even if the walls of these hairs are extremely thin.

Variety b. This variety is found on the mandibles (figs. 7, 8, and 6 B, b_1, b_2 and b_4) and on the pharyngeal plate (figs. 9 B and 10, b_3). These are short, stout hairs with thick walls. At the proximal end of the mandible (fig. 7, b_1) they are usually bent and about a half of each one lies buried in the chitin surrounding the socket (fig. 1 B, b_1).

The chitin (*Ch*) at this place is extremely thick, causing the sense fibers (*SF*) to be very long. In all sections passing through this group of hairs the sense cells (*SC*) are discernible, but their fibers are usually severed because an entire cell rarely lies in the same plane in which the section was cut. In the 20-day-old pupa the hypodermis (*Hyp*) is comparatively thin.

On the ventral side of the mandible (fig. 8, b_2) these hairs are straight, but have the same structure as the ones just described, except that the sockets (fig. 1 C) are sunk only slightly beneath the outer surface of the chitin.

Those on the pharyngeal plate (fig. 1 D, b_3) are slightly larger than the ones just described. These are slightly curved and most of them point toward the mouth. Their sockets stand a little above the level of the chitin, and the walls at their tips are not so thick as at the bases. The sense fibers run nearly all the way to the tips of the hairs. Beneath the pharyngeal plate in the 21-day-old pupæ, the hypodermis (*Hyp*) is extremely thick and its cells are so grouped together that each hair seems to be innervated by a large group of cells, but in all such cases no sense fibers were seen running from the groups to the hairs. After spending considerable time it was ascertained that the sense cells (*SC*) seldom lie in the middle of the hypodermis, but near its inner edge. They are usually cut transversely, and for this reason the fibers are rarely seen connecting with the cell bodies.

The hairs (figs. 1 E and 7, b_4) at the distal ends of the mandibles are the longest ones of this variety, and their tips are blunt, while the tips of the others are sharp. In structure they are like those on the ventral side of the mandibles (fig. 1 C, b_2), except that they are slightly curved.

Variety c. This variety, found on the head and all the head appendages, varies from the smallest hairs on the antennæ (fig. 2 A) to the largest on the maxillæ (fig. 2 U). Figure 2 A and B represent the smallest and largest on the flagellum of a worker bee, and figure 2 C those on the scape. All of those on the maxillæ are of about the same size (fig. 2 D and E), but when first observed those on the maxillary palpi (fig. 2 E) appear to be the smallest. Those on the labial palpi (fig. 2 F) are slightly larger than those on the maxillæ. Those on the mandibles (fig. 2 G) and paraglossæ (fig. 2 H) are of the same size and are considerably larger than the ones just described. On the cervical plate (fig. 10, *CvPl*) these hairs (fig. 2 I to K) vary considerably in size. Just inside the buccal cavity a few innervated hairs (fig. 2 L) were found; also a few (fig. 2 M) on the head near the

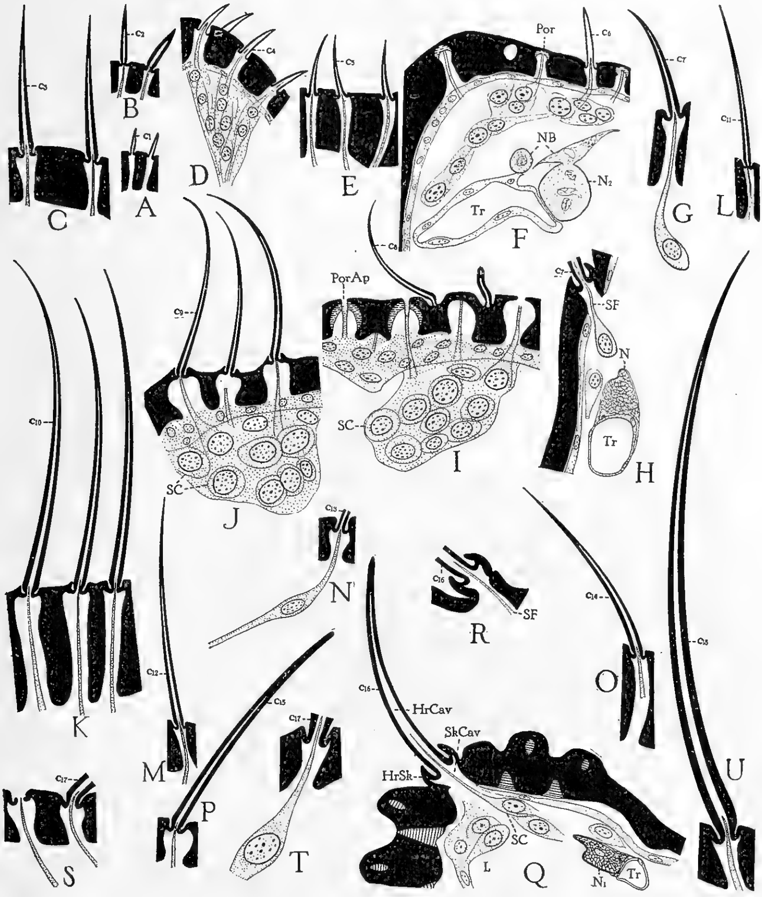

FIG. 2.—Internal anatomy of variety *c* of spinelike, innervated hairs of worker honey bees, x 580. A, smallest and B, largest of these on flagella of antennæ; C from base of scape of flagellum; D from maxilla; E from maxillary palpus; F from labial palpus; G from proximal end of mandible; H from base of paraglossa; I to K from cervical plate; L from just inside buccal cavity; M from side of head, near base of mandible; N from median line on top of head, over pharyngeal plate; O from palpiger; P from side of mentum; Q from middle of glossa, the hair being from a whole mount and the hair socket (*HrSk*) from section; R from tip of glossa; S from dorsal and T from ventral surface of labrum; U from tip of maxilla. All of these hairs, except c_1 to c_3, may be located by referring to figures 7, 8, 9 C and 10. They were taken from pupa and imago workers of various ages. See page 54 for explanation of abbreviations.

base of the mandibles, and a few (fig. 2 N) on top of the head directly above the pharyngeal plate (fig. 10). The following figures represent the innervated hairs found in sections through the palpigers (figs. 2 O, 7, *Plg*) ; on the side of the mentum (figs. 2 P, 7, c_{15}) ; on the glossa (fig. 2 Q and R) ; on the labrum (fig. 2 S and T) ; and on the labial palpi and maxillæ (fig. 2 U).

In structure these various hairs are all alike in that they have thick walls, sharp points and distinct sockets. The sockets of the smaller hairs usually lie slightly beneath the external surface of the chitin, as shown in figure 2 D, while those of the larger hairs may lie a little beneath the external surface of the chitin, as seen in figure 2 G, or above the surface of the chitin, as shown in figure 2 Q. The chitin connecting the base of the hair with the socket is always more or less

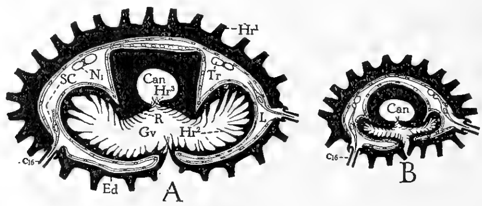

FIG. 3.—Cross-sections through glossa or tongue of a worker honey bee, showing internal anatomy including groove (*Gv*), canal (*Can*) inside rod (*R*), sense cells (*SC*), nerve (N_1), trachea (*Tr*) ; lumen (*L*), and bases of pseudohairs (Hr^1 to Hr^3) and innervated hairs (c_{16}), x 230. A, through middle and B through tip of glossa.

flexible, so that the least movement of the hair mechanically irritates the end of the sense fiber.

The sense cells belonging to all the hairs drawn were not seen, but the sense fibers were seen as shown. A hair was never regarded a sense organ unless a sense fiber was seen running into it. The sense cells are always spindle-shaped and the sense fibers (fig. 2 H, *SF*) never run far into the hairs.

The hairs at the tip of the tongue of the honey bee (fig. 7, *Gls*) have been regarded as gustatory in function, but as yet no one has ever shown that they are innervated. In cross-sections through the middle of the tongue the sense cells (fig. 2 Q, *SC*) are generally discernible, but owing to the poor fixation only traces of them may be seen in the tip of the tongue, although the sense fibers (fig. 2 R, *SF*) are usually visible. On either side of the tongue a nerve (fig. 2 Q, N_1) and a trachea (*Tr*) are always present. They lie side by side and are fastened together with connective tissue. Branches from

the nerve are given off now and then which run toward the sense cells, but the actual connection of them with the cells was not observed. The internal anatomy of the tongue is best understood by referring to the semidiagrammatic figure 3 A and B. Figure 3 A is through the middle of the tongue, while 3 B is through the tip.

(b) PEGLIKE HAIRS

Two varieties of peg-shaped hairs occur on the maxillæ and labial palpi. To compare them with those found on the antennæ, two of the latter have been drawn.

Variety d. Figure 4 A and B represent the smallest and largest pegs seen on the flagellum of a worker bee. The chitin at the tips is about as thick as elsewhere. Other observers state that the chitin at the tips of these hairs is much thinner than elsewhere. This is ap-

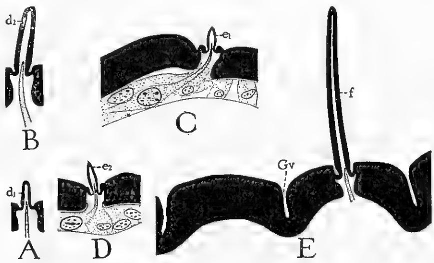

FIG. 4.—Internal anatomy of varieties *d*, *e* and *f* of peglike, innervated hairs of worker honey bees, x 580. A, smallest and B, largest of pegs on flagella of antennæ; C from maxilla; D from labial palpus; E from outer surface near tip of maxilla. These hairs, except d_1 and d_2, may be located by referring to figures 7 and 8.

parently true when a bright light is used, for the chitin is so nearly transparent at the tip that it appears thinner than where it is darker. When these hairs are carefully observed through the highest lenses and with less light, it seen that the chitin at their tips is about as thick as at their bases.

Variety e. The peglike hairs on the maxillæ (figs. 4 C, 7 and 8, e_1) and labial palpi (4 D and 8, e_2) are similar in structure to those on the antennæ. The following slight differences may be pointed out. Those on the mouth-parts are never so large as those on the antennæ. Their tips are less blunt and their sockets project slightly above the surface of the chitin, while the sockets of those on the antennæ lie a little below the external surface of the chitin.

Variety f. These are found on the distal ends of the maxillæ and labial palpi (figs. 7 and 8, *f*). They are long and slender, usually

slightly curved, and have blunt tips (fig. 4 E). The chitin of the distal half of the maxilla contains many long longitudinal and deep grooves (fig. 4 E, *Gv*). These grooves cause the wide maxillary lobe to be quite flexible, thus enabling the bee to fold the maxillæ around the other mouth-parts.

Judging from the anatomy of all the spinelike and peglike hairs described in the preceding pages, it does not seem possible that they can serve either as gustatory or as olfactory organs because the odoriferous particles in the air and the liquids carrying substances in solution could not pass through the hard and thick walls of the hairs to stimulate the ends of the nerves. Since insects cannot feel weak mechanical stimuli through their chitinous integuments without some kind of a sensory organ, it seems that all of these innervated hairs are well adapted to serve as tactile organs. The sense of touch is further discussed on page 39.

2. Structure of the Olfactory Pores

Olfactory pores were found on the mandibles (figs. 7 and 8, *Md, Por*), maxillæ (fig. 8, *Mx*), labial palpi (fig. 7, *LbPlp*), tongue (fig. 7, *Gls*), side of head, in the buccal cavity, on the cervical plate and on the bases of the scapes of the antennæ. In structure all of these are similar, and they are identical with those which have already been found on the legs, wings and sting.

Figure 5 A represents one of the largest olfactory pores found on the mandibles. The chitin (*Ch*) of the mandibles is always very thick, making the necks (fig. 5 E, *NkFl*) of the small pores long and slender. A chitinous cone (fig. 5 A, *Con*) is always present. In pupæ these cones are usually connected with a hypodermal secretion (*HypS*), but in adults this secretion is never seen. Sometimes this secretion fills the entire pore, and it generally contains streaks running from the hypodermis (*Hyp*) to the cone. Unless all stages of these organs are critically studied, it is easy to imagine that this secretion is a permanent structure of the pores. This explains why Janet (1911) regards this substance as a part of the organ, and why he thinks that the cavity of the pore is filled with two or three concentric cylinders. In studying the same organs in Coleoptera, the writer (1915, p. 422) shows that the cones are a later formation than the chitin surrounding them and that the hypodermal secretion does not begin to form the cones until the sense fibers have connected with the pore apertures. The writer has also shown

that the sense cells begin to differentiate when the hypodermal cells begin to form the chitin. It is thus seen that by the time the chitin is of considerable thickness, the sense fibers have united with the pore apertures and the formation of the cones has begun. There are two possible functions of the cones: (1) to strengthen the chitin forming the bottoms of the flask-shaped pores, and (2) to insure firm attachments for the peripheral ends of the sense fibers. The latter function

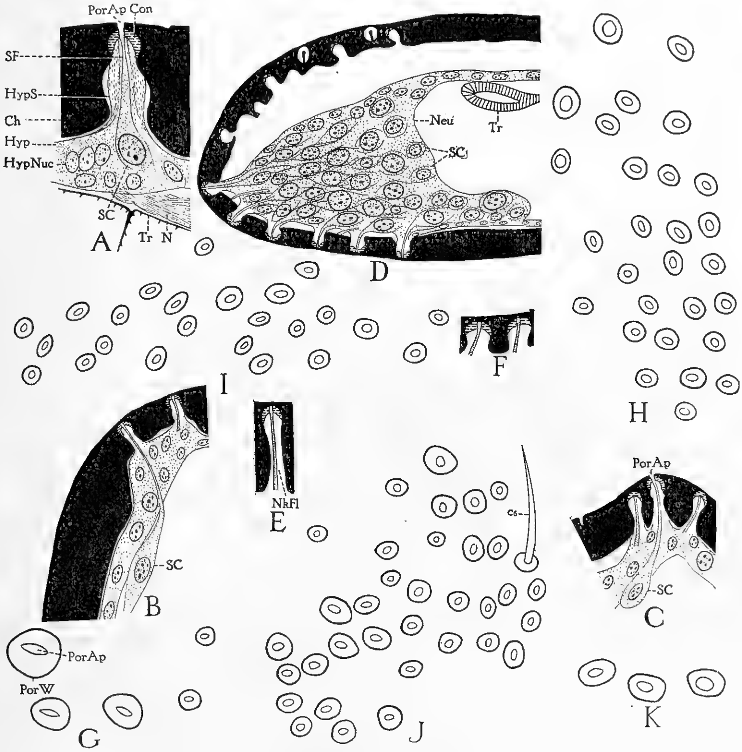

FIG. 5.—Internal anatomy and superficial appearance of olfactory pores on mouth-parts, head and cervical plate of worker honey bees, x 580. A to F, cross-sections; A, one of largest olfactory pores from mandible of a 20-day-old pupa, showing sense cell (*SC*), pore aperture (*PorAp*), and hypodermal secretion (*HypS*) forming the cone (*Con*); B, two olfactory pores and one sense cell from base of glossa; C, three olfactory pores and one sense cell from maxilla; D, a group of olfactory pores and sense cells in labial palpus; E, an olfactory pore from side of head; F, two olfactory pores from buccal cavity; G to K, superficial appearances: G, three of largest olfactory pores on mandible; H, one of the two groups of olfactory pores on base of tongue; I, group of olfactory pores on maxilla; J, group of olfactory pores on labial palpus; K, three of largest olfactory pores on cervical plate. These pores may be located by referring to figures 7, 8, 9 C and 10. See page 54 for explanation of abbreviations.

seems absolutely necessary for the following reason. In adult bees the hypodermis is quite thin and in certain places has practically disappeared. It no longer is firmly fastened to the chitin and it can no longer hold the sense cells in their proper places. If the sense fibers were fastened to the chitin only by the ends of their walls and not by the entire peripheral ends being surrounded by the chitinous cones, the sense fibers would break loose from the pore apertures. Firm attachments for the sense fibers in spiders (McIndoo, 1911) are not necessary, because the sense cells lie in a thick hypodermis which persists throughout the lives of the spiders; and furthermore, cones are not formed, because the pore apertures pass entirely through the cuticula, so that the sense fibers join the apertures on the internal surface of the integument.

The olfactory pores on the base of the tongue (fig. 5 B), maxillæ (fig. 5 C), labial palpi (fig. 5 D), and the smallest on the mandibles, are of about the same size as those on the wings. The spindle-shaped sense cells are easily seen; but owing to the small size of the pores, the pore apertures are rarely discernible. Beneath the group of pores on the labial palpus, the sense cells (fig. 5 D, *SC*) occupy about a half of the space in the appendage. Fig. 5 E and F represent, respectively, the sizes of the pores found on the side of the head near the base of the mandible, and just inside the buccal cavity. A nerve (N_2) and a trachea (fig. 2 F, *Tr*) run near the group of sense cells through the labial palpus. Figure 2 I shows the structure of the largest olfactory pores on the cervical plate. These are equally as large as the largest ones on the mandibles, but the smallest ones are never so small as the smallest on the mandibles.

Under the microscope with transmitted light the olfactory pores appear as bright spots. Each bright spot is surrounded by a dark line, the pore wall (fig. 5 G, *PorW*). Outside this line the chitin is generally dark in color, while inside of it the chitin is almost transparent, and at the center there is an opening, the pore aperture (*PorAp*).

Figure 5 G to K represent, respectively, the sizes of the superficial appearances of the pores on the mandible, tongue, maxilla, labial palpus, and cervical plate.

To learn how well the mandibles are provided with sense organs, the reader is referred to figure 6 A. This is a semidiagrammatic drawing taken from one cross-section through the middle of a mandible of a 20-day-old worker pupa. The details of the hypodermis

(*Hyp*) were taken from another section in which the hypodermal cells were better fixed. Any section through the middle of a mandible invariably shows from two to four large pores, from one to three small pores, and one or more innervated hairs. The nearer the distal end of the mandible a section is taken, the fewer the large pores and

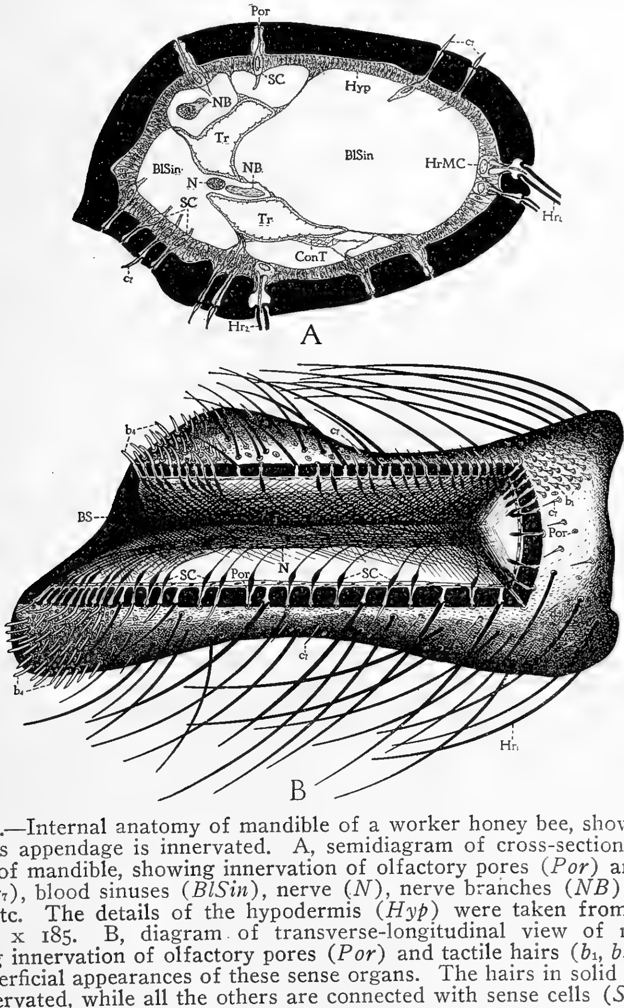

FIG. 6.—Internal anatomy of mandible of a worker honey bee, showing how well this appendage is innervated. A, semidiagram of cross-section through middle of mandible, showing innervation of olfactory pores (*Por*) and tactile hairs (c_7), blood sinuses (*BlSin*), nerve (*N*), nerve branches (*NB*), tracheæ (*Tr*), etc. The details of the hypodermis (*Hyp*) were taken from another section, x 185. B, diagram of transverse-longitudinal view of mandible, showing innervation of olfactory pores (*Por*) and tactile hairs (b_1, b_4 and c_7), and superficial appearances of these sense organs. The hairs in solid black are not innervated, while all the others are connected with sense cells (*SC*). See page 54 for other abbreviations.

the greater the number of small pores and innervated hairs it shows. Large hypodermal cells, called hair-mother cells (*HrMC*), are often seen beneath the largest hairs on the mandibles. They send processes

into the hairs through which the cellular secretion passes to form the hairs. At first sight these cells resemble sense cells, but a further study shows that they are quite different. The tracheæ (*Tr*) are suspended to the hypodermis by connective tissue (*ConT*) and the nerves (*N*) are suspended to the tracheæ in the same manner. All the space not occupied by the enumerated structures may be called blood sinuses (*BlSin*).

A still better idea of how well the mandibles are innervated is gained by referring to figure 6 B. This is a transverse-longitudinal diagram showing the main nerve (*N*) sending off branches to the sense cells (*SC*) belonging to the olfactory pores (*Por*) and the three varieties of innervated hairs (b_1, b_4 and c_7).

3. Disposition of the Innervated Hairs

In the preceding pages the distribution and number of the sense organs on the mouth-parts have been briefly discussed in connection with their anatomy. Now since we have classified these organs on the basis of their structure, their disposition will be given in detail. In counting the number of sense organs herein discussed, five individuals each of workers, queens and drones have been used. Owing to some of the parts being mutilated and concealed, a few of the groups of hairs and olfactory pores could not be counted; so it was necessary to estimate the number in such groups. It was not possible to count all the sense organs on the mandibles on account of the opaqueness and rotundity of these appendages; therefore, only estimates of all the sense organs on the mandibles except variety b_1 of the hairs will be given.

(a) SPINELIKE HAIRS

Variety a. This variety is found only on the epipharynx. The epipharynx is a large three-lobed appendage (fig. 9 A, *Ep*) depending from the roof of the preoral cavity (fig. 10, *Ep*) just in front of the mouth (*Mo*). It is movable up and down and serves to close the mouth opening. These hairs (fig. 9 A, *a*) are arranged in two groups at the base of the epipharynx, a group lying on either side of the high, vertical, keel-shaped median lobe (*K*) of the so-called dorsal tongue. For workers, the number of hairs in a single group varies from 41 to 79; in a pair of groups, from 83 to 147, with an average of 104 hairs for one worker. For queens, the number of hairs in a single group varies from 24 to 92; in a pair of groups, from 55 to 176, with an average of 103 hairs for one queen. For drones, the number of hairs

in a single group varies from 40 to 74; in a pair of groups, from 82 to 134, with an average of 101 hairs for one drone. It is thus seen that each caste possesses virtually the same number of hairs on the epipharynx.

Variety b. Hairs marked b_1 are found only at the proximal end of the mandible on the outer, dorsal corner (fig. 7, b_1). There are about 85 in each group.

Hairs marked b_2 occur only on the inner surface of the mandible, on an elevated ridge (figs. 8 and 10, *Rg*) just posterior to the biting surface (*BS*). Each mandible has a single row of these organs, consisting of about five hairs.

Hairs marked b_3 are present only on the pharyngeal plate. This plate is a strong chitinous structure forming the anterior part of the floor of the pharynx (fig. 10, *PhPl*). It has two terminal points (figs. 9 B and 10, *TP*) hanging downward over the lower rim of the mouth and two long chitinous rods which are attached to the sides of the plate. These rods (*PhPlR*) run around the sides and to the top of the pharynx (*Ph*), where they are fastened to muscles which in turn are attached to the chitin on the top of the head. The posterior part of the pharyngeal plate is arched upward, forming two large domes, with a deep groove between the domes. The hairs under discussion are grouped on these domes. Some of the hairs point forward, some backward and others toward the roof of the pharynx. The number of hairs in the groups varies only slightly. As an average for workers, there are 90 hairs on a pharyngeal plate; for queens, 74 hairs; and for drones, 66 hairs. It is thus seen that these hairs in the three castes vary considerably in number.

Hairs marked b_4 (fig. 7) are found only on the outer surfaces of the mandibles at the tips. They are arranged irregularly, except that one row follows the contour of the biting edge. The hairs in this row project slightly beyond this edge and often curve over it. There are probably 100 of these hairs on each mandible.

Variety c. Hairs marked c_1 are present on the flagella of the antennæ where there are no pore plates. Those marked c_2 are usually found between the pore plates. Those marked c_3 occur only on the scapes of antennæ.

Only a few hairs marked c_4 (figs. 7 and 8) occur on each maxilla. Twenty-five marked c_5 are found on the base of each maxillary palpus. Only a few marked c_6 are present among the olfactory pores on the inner surface of the labial palpus. About 75 marked c_7 occur on each mandible, the most of them being on the outer surface, and about 40

of the same kind are found at the base of each paraglossa on the dorsal side. About 35 hairs are present on each cervical plate, the most of them being the ones marked c_{10}. This plate is a heavy chitinous structure on the "throat" of the bee (figs. 9 C and 10, *CvPl*), and the writer has called it the "cervical" plate on account of its

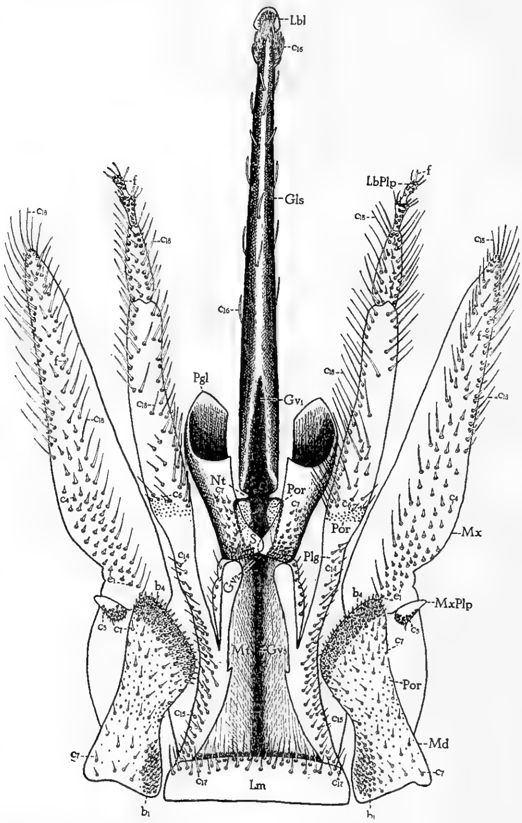

FIG. 7.—Diagram of mouth-parts of a worker honey bee spread out flat, showing disposition of innervated hairs (b_1, b_4, c_4 to c_7, c_{14} to c_{18}, e_1 and f) and olfactory pores (*Por*), on dorsal surfaces of glossa (*Gls*), paraglossa (*Pgl*), palpigers (*Plg*), mentum (*Mt*), and labrum (*Lm*), on inner surfaces of labial palpi (*LbPlp*), and on outer surfaces of maxillæ (*Mx*) and mandibles (*Md*), x 25. All the hairs shown are innervated, and the pseudo-hairs on the glossa have been omitted. See page 54 for other abbreviations.

position. It has two deep folds, in the anterior one (fig. 9 C and 10, *F*) of which may be seen the tactile hairs (c_8 to c_{10}) and olfactory pores (*Por*). A few scattered, innervated hairs were found just inside the buccal cavity, a few on the side of the head and a few on

TABLE VIII

Disposition of Innervated Hairs herein Discussed

Caste	Spinelike Hairs																Peglike Hairs			
		Variety *b*				Variety *c*												Variety *e*		
	Variety *a* on epipharynx	b_1 on mandibles	b_2 on mandibles	b_3 on pharyngeal plate	b_4 on mandibles	c_1 to c_3 on antennæ	c_4 on maxillæ	c_5 on maxillary palpi	c_6 on labial palpi	c_7 on mandibles and paraglossæ	c_8 to c_{10} on cervical plate	c_{11} to c_{13} in buccal cavity; on sides and top of head	c_{14} to c_{15} on palpigers and mentum	c_{16} on glossæ	c_{17} on labrum	c_{18} on maxillæ and labial palpi	Variety d_1 and d_2 on antennæ	e_1 on maxillæ	e_2 on labial palpi	Variety *f* on maxillæ and labial palpi
Drone...	101	....	....	66	....	......	....	....	....	....	....	....	....	...	....	......	......	......	......	....
Worker .	104	170	10	90	200	Many	Few	50	Few	230	35	Few	Several	83	Several	Many	Many	100	Few	Several
Queen...	103	....	....	74	....	......	....	....	....	....	....	....	....	...	....	......	......	......	......	....

TABLE IX

Disposition of Olfactory Pores herein Discussed and Those previously Found elsewhere on Honey Bee

Caste	Number of pores on wings	Number of pores on legs	Number of pores on sting	Number of pores on mandibles	Number of pores on glossa	Number of pores on labial palpi	Number of pores on maxillæ	Number of pores on cervical plate	Number of pores in buccal cavity	Number of pores on sides of head	Number of pores on scapes of antennæ	Total number of pores
Drone......	1998	606	....	204??	31	46	40	23	Few??	Few??	Few??	2948+
Worker.....	1510	658	100	300?	48	68	56	26	Few	Few	Few	2766+
Queen......	1310	450	100	210??	32	48	40	24	Few??	Few??	Few??	2214+

top of the head (fig. 10, c_{13}). Several were seen on each palpiger (figs. 7 and 8, c_{14}) and several, marked c_{15}, on the ventral surface and sides of the mentum. Eighty-three hairs marked c_{16} were counted on the tongue. The most of these lie on the ventral side. Several innervated hairs marked c_{17} were seen on each side of the labrum near the anterior edge. All the large hairs marked c_{18} on the maxillæ and labial palpi seem to be innervated.

(b) PEGLIKE HAIRS

Variety d. Those marked d_1 and d_2 are found only on the flagella of the antennæ.

Variety e. Those marked e_1 are found on both sides of the maxillæ near the maxillary palpi. There are perhaps 50 on each maxilla. Only a few marked e_2 are present on the base of each labial palpus.

Variety f. Several marked f occur at the distal end of each maxilla and labial palpus.

In conclusion under this heading it is seen that all the true hairs on the tongue are innervated, while practically all on the maxillæ, labial palpi, palpigers, paraglossæ and mentum are connected with nerves. All of those near the anterior edge of the labrum and all on the mandibles, except two varieties of large hairs (figs. 6 B, Hr_1 and 10, Hr_2), are also connected with sense cells.

Table VIII is a tabulated summary of the disposition of the innervated hairs herein discussed. The blank spaces mean that hairs were not looked for on the appendages recorded.

4. Disposition of the Olfactory Pores

Olfactory pores (figs. 7 and 8, *Por*) were found irregularly distributed over the entire surface of the mandibles (*Md*), except on the biting surfaces (*BS*) and between the two ridges (*Rg*). Very few occur on the proximal half of this appendage, while they are quite abundant on the distal half. There are at least 150 on each mandible of the workers.

On the tongue (fig. 7, *Gls*) olfactory pores were found only on the dorsal side at the base. These are arranged in two groups, each group being located on a prominence just posterior to the notch (*Nt*). A groove (Gv_2) connecting with the two notches runs between the two prominences and continues as a shallow depression (Gv_3) to the base of the mentum (*Mt*). The number of pores in either group on any given tongue is almost constant, and the individual variations

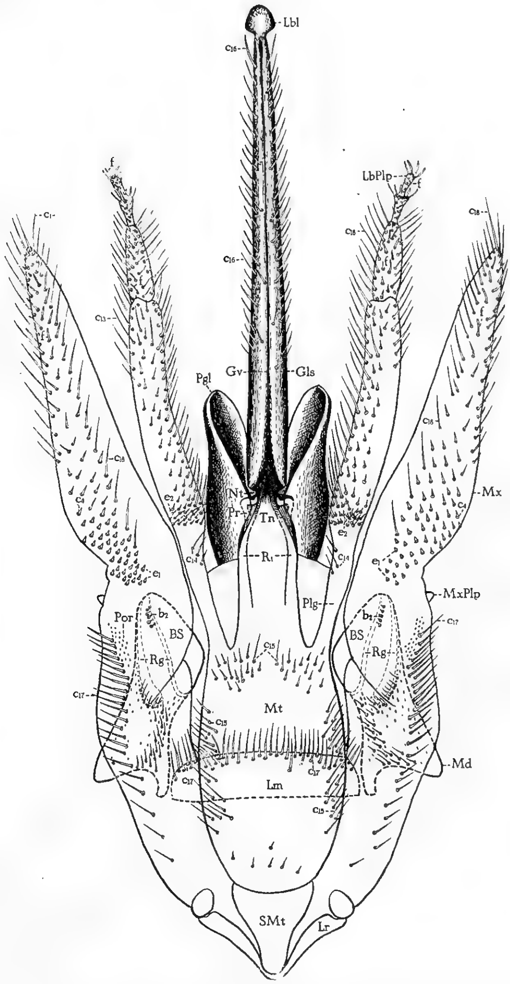

Fig. 8.—Diagram of mouth-parts of a worker honey bee spread out flat, showing disposition of innervated hairs (b_2, c_4, c_{14} to c_{18}, e_1, e_2, and f) and olfactory pores (*Por*) on ventral surfaces of glossa (*Gls*), palpigers (*Plg*), mentum (*Mt*) and labrum (*Lm*), on outer surfaces of labial palpi (*LbPlp*), and on inner surfaces of maxillæ (*Mx*) and mandibles (*Md*), x 25. The mandibles and labrum are seen by looking through the other appendages. All the hairs shown are innervated, and the pseudo-hairs on the glossa have been omitted. See page 54 for other abbreviations.

are insignificant, but the caste variations are sufficiently large to indicate that queens and drones do not have as strong likes and dislikes for foods as do workers. As an average for workers, there are 48 pores on each tongue; for queens, 32 pores; and for drones, 31 pores.

On the inner surface of each labial palpus (fig. 7, *LbPlp*) a group of olfactory pores (*Por*) extends entirely across the base of this appendage. These groups are always present and the individual variations are slight. As an average for workers, there are 34 pores on each labial palpus; for queens, 24 pores; and for drones, 23 pores.

On the inner surface of each maxilla (fig. 8, *Mx*) near the maxillary palpus (*MxPlp*) there is a group of olfactory pores (*Por*). This group is never absent and the individual variations in number of pores in it are slight. As an average for workers, there are 28 pores on each maxilla; for queens, 20 pores; and for drones, 20 pores.

A group of olfactory pores (figs. 9 C and 10, *Por*) is always present on the cervical plate (*CvPl*). As an average for workers, this group contains 26 pores; for queens, 24 pores; and for drones, 23 pores.

A few olfactory pores were seen in each of the following places: just inside the buccal cavity, on each side of the head, and on the base of the scape of each antenna.

Table IX is a tabulated summary of the disposition of the olfactory pores herein discussed and those previously found elsewhere on the honey bee by the writer. The plus sign, " +," means that there were more than the number recorded. The single question mark, " ?," means that the pores were estimated; and the double question mark, " ??," means that the numbers recorded were computed by using the ratios of the total number of pores on the other mouth-parts as a basis.

It is thus seen that drones as an average have a few more than 2,948 olfactory pores; workers a few more than 2,766, and queens a few more than 2214 olfactory pores.

In various papers the writer has shown experimentally that the olfactory pores on the legs and wings of hymenopterous and coleopterous insects receive odor stimuli, and it is only reasonable to suppose that the same organs on the mouth-parts perform the same or a similar function, although we have no way of knowing whether the sensation produced is that of smell or that of taste. Judging from the anatomy of the organs, we are inclined to call the sensation smell, but judging merely from the experiments to determine whether

bees have likes and dislikes in regard to foods, the indications are that bees have a sense more or less similar to our sense of taste.

To ascertain whether the elimination of the olfactory pores on the wings would produce any effect upon the ability of bees to discriminate between foods, the wings of 20 workers were pulled off at their articulations. Such an operation eliminates all the sense organs on the wings, and the writer has previously shown that bees without wings behave normally in all respects except that they respond more slowly to odor stimuli. These 20 bees were fed pure cane-sugar candy and cane-sugar candy containing strychnine, as described on page 14. At first a few ate a little of the poisoned candy, but after that not a single bee was seen eating it, but they ate the pure cane-sugar candy normally. This indicates that when the 1500 pores on the wings are prevented from functioning, the remaining 1200 pores found elsewhere on a worker are sufficient to enable the bee to distinguish the candy containing strychnine from the pure candy. These experiments showed that further experimentation along this line was useless.

5. The Tactile Sense of the Honey Bee

Since the innervated hairs herein discussed certainly cannot serve either as olfactory or as gustatory organs, there still remain only two known senses which we might consider in connection with these hairs. (1) An auditory function has never been attributed to any of these hairs, but similar hairs on spiders have been called auditory hairs. We need not consider the sense of hearing further. (2) The tactile sense seems to be the most plausible function to attribute to them, although no experiments were performed to test this view.

If we call these innervated hairs tactile hairs, we can easily explain many of the activities of bees. Since bees are covered with a hard chitinous integument, a person often wonders how it is possible that they can perform their many duties of caring for the brood, building comb, etc., unless they have an acute sense of touch. They certainly cannot feel weak mechanical stimuli through the integument as we do through the skin, and for this reason various kinds of hairs have become innervated.

Instead of the innervated hairs on the tongue being gustatory in function, they are certainly used chiefly in examining food as to whether it is solid or liquid. If the food should be solid and must be dissolved before being eaten, these hairs perceive stimuli which cause a copious flow of saliva. If the food should be a solid and

not to be dissolved, it is first probably examined by the maxillæ and labial palpi before being seized by the mandibles. By means of the many sense hairs covering the mandibles, these appendages are able at any moment to perceive the size, shape and firmness of the food; and when the food particles are sufficiently small to be swallowed, they are placed upon the dorsal side of the mentum (fig. 7, *Mt*). While watching a bee eat, it is easily observed by using a pair of binoculars that the mentum (fig. 10, *Mt*) may be moved in three directions. The forward and backward movement is most noticeable. The second movement is up and down and the third is a sidewise

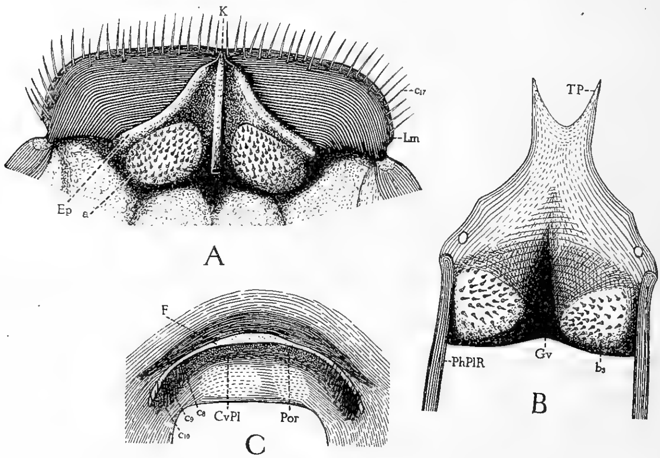

FIG. 9.—Superficial appearances of the innervated hairs (a, c_{17}, b_3, c_8 to c_{10}) on the epipharynx, labrum, pharyngeal plate and cervical plate, and of the olfactory pores (*Por*) on the cervical plate of worker honey bees. A, ventral surfaces of labrum (*Lm*) and epipharynx (*Ep*), showing two groups of variety *a* of innervated hairs on prominences at base of epipharynx, x 45. B, inner surface of pharyngeal plate, spread out flat, showing two groups of variety *b* of innervated hairs (b_3) on dome-shaped prominences at posterior end of this plate, x 45. C, outer surface of cervical plate (*CvPl*), spread out flat, showing a group of variety *c* of innervated hairs (c_8 to c_{10}) on either side of this plate with a long group of olfactory pores (*Por*) between them, x 50. For other abbreviations see page 54.

one. The mentum, including the appendages attached to it, acts like a small crane which may be moved backward and forward, up and down, and from side to side to a limited degree. The mentum is moved forward when the food particles are to be conveyed from the mandibles to the mouth. After these particles have been placed upon the mentum posterior to the paraglossæ, the mentum is moved backward and upward through the buccal cavity (*BCav*) until the particles are at the mouth opening (*Mo*). The tactile hairs inside

this cavity may be stimulated by the particles touching them, thereby informing the bee that the food is ready to be swallowed. The presence of the food in the mouth is made known to the bee by means of the hairs on the epipharynx (*Ep*) coming in contact with it. The act of swallowing is facilitated by means of the epipharynx pushing the food into the mouth. This act is explained by the fact that the fleshy-like epipharynx may be moved up and down by a set of longitudinal muscles (M_3), and it is also capable of completely closing the mouth opening by the longitudinal (M_3) and transverse muscles (M_{10}) working in unison.

Should a particle of food, too large to pass through the narrow œsophagus (fig. 10, *E*), be swallowed, it would be stopped when it reached the hairs (b_3) on the pharnygeal plate (*PhPl*) by means of the transverse muscles (M_{10}) contracting, thereby forcing it to the exterior. It is thus seen that the hairs on the pharyngeal plate act as a safety device to prevent pieces of solid food, too large to go through the œsophagus, from passing into the pharynx (*Ph*).

The tactile hairs on the maxillæ and labial palpi are of the utmost importance to workers while caring for the brood and in examining the comb, etc. The hairs marked b_4 on the mandibles perhaps play their greatest rôle while these appendages are being used for building comb. Regarding these as tactile hairs, it is easy to understood how bees are able to mold the walls of all the cells of uniform thickness.

6. How Bees Eat Liquid Foods

While watching a bee eat honey under a simple microscope, it will be observed that the maxillæ remain almost stationary while the mentum, carrying the tongue, paraglossæ and labial palpi, is being moved forward and backward, up and down through the buccal cavity between the maxillary bases as if the honey were being either pumped or sucked up into the mouth. It is now generally believed that liquid foods pass up the glossa or tongue by capillary attraction and are then sucked into the mouth. This view seems to be the only plausible one, and after completely understanding this method it is seen that Nature could not have devised a better plan. If a bee ate only liquid foods, a proboscis connecting directly with the mouth would be a better apparatus, but we well know that bees eat more or less of solid food in the form of pollen.

As a typical example to serve all purposes, let us suppose that a bee is about to eat candy containing a small amount of quinine, and let us suppose that the bee cannot smell the quinine in the candy.

The bee probably first recognizes the candy as food by smelling it before touching it. After smelling the candy the first reaction of the bee is to move toward it, to extend the tongue and to examine the food with the sense hairs on the tip of the tongue. The extending of the mentum (fig. 10, *Mt*) is accomplished by muscles not shown in figure 10. The tongue is unfolded from beneath the mentum by the contraction of a pair of muscles (M_2), attached to a pair of hard chitinous processes (*Pr*). The tongue is folded beneath the mentum by means of two muscles (fig. 10, M_1) pulling on a pair of chitinous rods (R_1) which are the two forks of the chitinous rod (*R*) extending the full length of the glossa through the center. When the tongue is extended and as quickly as the bee recognizes that the food must be dissolved, the salivary syringe (*SS*) forces its supply of saliva to the exterior, at the point marked *S* in figures 7 and 10. The saliva runs forward along the groove between the two groups of olfactory pores (fig. 7, *Por*) and passes around the notches (*Nt*) to the ventral side of the tongue, where it enters the proximal end of the groove (fig. 8, *Gv*) which extends the full length of the glossa. The extreme proximal end of the groove is wide and shallow, and at this place there is no distinction between the groove (fig. 3 A, *Gv*) proper and the canal (*Can*) formed by the rod (*R*). Not far from the notches the wide groove becomes narrow and deep and the canal is distinctly separated from the groove. A portion of the ventral surface of the mentum extends as a fleshy tongue (fig. 8, *Tn*) along the roof and through the center of the wide groove. The end of this tongue terminates where the canal is separated from the groove. Now the saliva, in traveling from the external opening of the salivary syringe on the dorsal side of the tongue to the ventral side of the tongue by capillary attraction, is guided into the canal by means of the fleshy tongue just described. From this place to the tip of the tongue the canal is completely separated from the groove by minute interlocking pseudo-hairs (fig. 3 A, Hr^3) which point toward the tip of the tongue. According to the law of capillarity the saliva, aided by the pseudo-hairs, passes through the canal as rapidly as oil climbs a wick. The saliva, after reaching the tip of the tongue, spreads over the surface of the spoon-shaped labellum (fig. 8, *Lbl*) which is used for scraping the candy. The scraping and changing of the sugar to liquid is facilitated by the many forked pseudo-hairs on the labellum. When the food is dissolved, it enters the groove at the tip of the tongue, passes through the entire length of the groove to the base of the tongue, where it then passes through the notches to the dorsal side of the tongue and

then along the groove (fig. 7, Gv_2) to the place marked X on the dorsal surface of the mentum (fig. 10).

While eating honey and syrup greedily, the distal half of the groove may be opened widely to the exterior so that the liquid may enter more rapidly. Since there are no muscles in the glossa, the only way to explain the opening of the groove is by supposing that the blood rushes

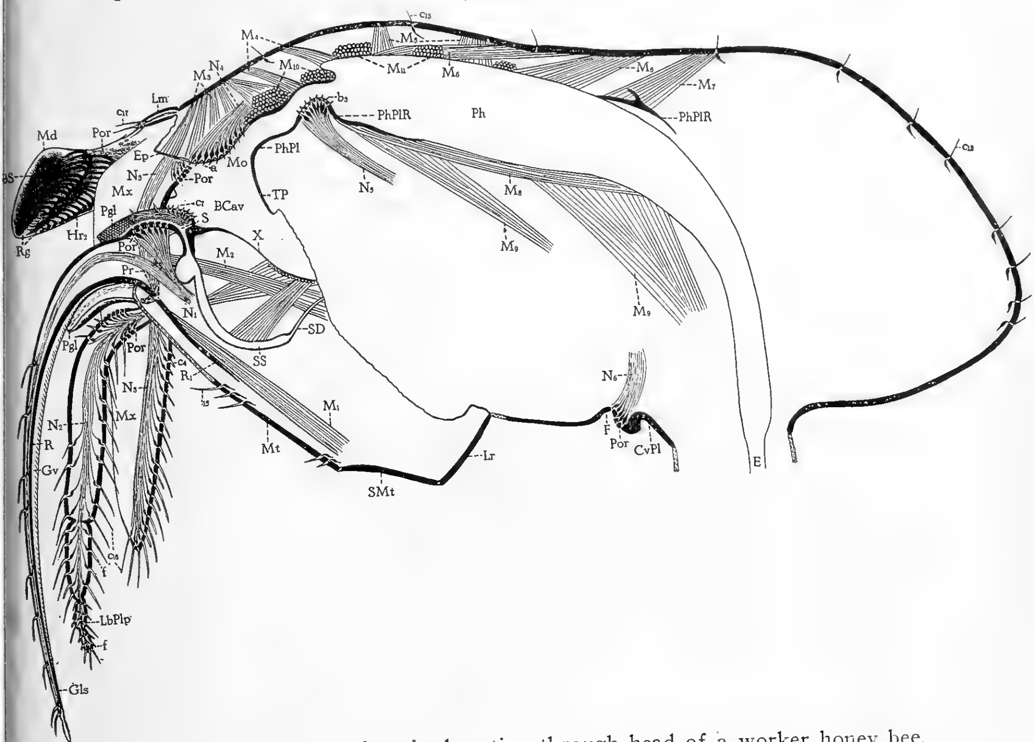

FIG. 10.—Diagram of sagittal section through head of a worker honey bee, slightly lateral to median line of head, pharyngeal plate (*PhPl*), epipharynx (*Ep*), labrum (*Lm*), cervical plate (*CvPl*), mentum (*Mt*), paraglossa (*Pgl*), and glossa (*Gls*). Diagrams of longitudinal sections of maxilla (*Mx*) and labial palpus (*LbPlp*), and of inner surface of right mandible (*Md*), are drawn in their approximate positions. This diagram is meant to show chiefly innervation of glossa by nerve marked N_1, labial palpus by nerve marked N_2, maxilla by nerve marked N_3, epipharynx by nerve marked N_4, pharyngeal plate by nerve marked N_5 and cervical plate by nerve marked N_6, and to show how foods are swallowed when elevated to mouth (*Mo*) at point marked X on mentum (*Mt*) by means of various combinations of contracting and relaxing of muscles (M_3 to M_{11}) attached to epipharynx, pharyngeal plate and walls of pharynx. Muscles marked M_1 and M_2 fold and unfold glossa respectively. For other abbreviations see page 54.

into this part of the tongue and the edges of the groove (fig. 3 A, *Ed*) are widely separated by blood-pressure. In sections the rod (*R*) is often everted to the outside of the tongue.

According to the law of capillarity the height to which a liquid rises in a tube varies inversely with the diameter of the tube. In other words, the smaller the tube the higher a liquid rises in it. Using a tube four times as long as the glossa and with the diameter equal to that of the average diameter of the groove in the glossa, water would rise to the top of the tube merely by capillary attraction. This demonstrates that liquids quickly pass through the groove, and the movement of them is increased by the aid of the many pseudo-hairs (fig. 3 A, Hr^2) lining the groove and by some of them interlocking at the extreme edges of the groove to exclude the outside air. These hairs point toward the base of the tongue, making the groove as capable of carrying liquids as a wick is of lifting oil from the bottom of a tall bottle.

At the proximal end of the groove the liquid is turned to either side of the glossa by the fleshy tongue (fig. 8, *Tn*), and is prevented from traveling further on the ventral side of the mentum by the shoulder which is formed by the two chitinous processes (*Pr*) projecting below the ventral surface of the glossa. The shallow groove (fig. 7, Gv_1) on top of the tongue probably serves to hold the excess of liquid when it has difficulty in following its proper course.

As soon as saliva mixes with the food, a chemical or physical change is effected, and this change perhaps liberates odors that were not smelled by the bee before the food was eaten. Again, the saliva might so affect the quinine in the food described on page 14 that the faintest odor imaginable could be detected by the pores on the base of the tongue, and also probably by those on the labial palpi and maxillæ. It must be remembered that while the liquids are passing from the ventral side to the dorsal side of the tongue, and *vice versa,* the paraglossæ close around the tongue, making a perfect tube, and the labial palpi close tightly against the paraglossæ, and the maxillary lobes are folded around all of these appendages. It is thus seen that the olfactory pores on the glossa, labial palpi and maxillæ are almost against the liquid as it passes to the base of the mentum, for, as already pointed out, the pores on the labial palpi and maxillæ lie on the inner surfaces of these appendages.

This closes the description of the rôle played by capillary attraction in carrying liquids from the tip of the tongue to the base of the mentum. The entire process is clear to the writer except where the saliva and liquid food pass around the base of the tongue. It is strange that both liquids can travel in opposite directions along the same route by no force other than capillarity. This is partially

elucidated by the fact that the paraglossæ, in closing tightly around the base of the tongue, make a perfect tube which connects the groove on the ventral side of the glossa with the one on the dorsal side of the same appendage, and perhaps most of the liquid food is sucked into the mouth from the cavity formed by the paraglossæ.

We are now ready to explain how the liquid is sucked into the mouth. Cross-sections through the head of the bee show that the pharynx (fig. 10, *Ph*) assumes various shapes, but the shape shown in figure 10 is the most typical. Just posterior to the hairs (b_3) on the pharyngeal plate, it expands into a large, saclike body, while its posterior end gradually becomes smaller and is called the œsophagus (E) where it enters the thorax. The walls of the alimentary tract, from the mouth to the honey stomach, were examined to see if they contain sense organs, but none was found other than those already described. Nerves running to the cervical plate (N_6), pharyngeal plate (N_5) and the epipharynx (N_4) were seen, but no other nerves were observed connected with the pharynx, although several muscles were traced from the pharynx to their places of attachment. A study of these muscles shows that the pharynx may be moved in at least six different ways as follows: Muscles marked M_4 pull it forward; M_5, upward; M_6 and M_7, upward and backward; M_8, directly backward; M_9, downward and backward; and M_{10} and M_{11} change the diameter of it. It will be seen that M_7 is attached to the pharyngeal plate rod (*PhPlR*) and M_8 is fastened to the pharyngeal plate. The contraction of either one of these muscles would enlarge the tube leading from the mouth to the pharynx. From the preceding description it is easily understood that by various combinations of these muscles the pharynx works like a powerful pump, and when the liquid food on the dorsal surface of the mentum is raised to the mouth opening, the suction from the pharynx draws it into the mouth as easily as a person draws into his mouth water held in the palm of the hand.

7. Summary of Sense Organs

Only two general types of sense organs were found on the mouth-parts of the honey bee. They are innervated hairs and innervated pores, called olfactory pores by the writer (1914a). Judging from their anatomy, the innervated hairs can serve only as tactile organs, and none of them are anatomically adapted to function either as olfactory organs or as gustatory organs. The writer has divided them into spinelike and peglike hairs. Both types vary considerably in size and structure. In size the spinelike hairs vary from the smallest

ones on the antennæ to the largest ones on the maxillæ and labial palpi; the peglike hairs, from the short and thick ones on the maxillæ to the saber-shaped ones on the labial palpi and maxillæ. The spine-like hairs were found on all the mouth-parts, pharyngeal plate, antennæ, in the buccal cavity, all over the head and on the cervical plate. The peglike hairs were observed only on the antennæ, maxillæ and labial palpi.

Judging from the disposition and innervation of the hairs under discussion, the tactile sense in the honey bee is highly developed. The application of this perception easily explains how bees are able to perform their many duties, such as caring for the brood, building comb, etc.

The act of eating liquid foods is accomplished by capillary attraction, and by the pumping force of the pharynx.

Olfactory pores were found at the bases of the tongue and labial palpi, on the maxillæ near the maxillary palpi, widely distributed over the mandibles, on the cervical plate, in the buccal cavity, on the sides of the head and on the scapes of the antennæ. Their structure is identical with that of the olfactory pores on the legs, wings and sting, and therefore their function should be the same.

DISCUSSION OF LITERATURE

A review of the literature pertaining to the sense organs on the mouth-parts and to the gustatory sense of insects shows so much confusion in regard to the names of the various sense organs and their probable functions that it is impossible to classify the various structures correctly. The present writer has separated all the sense organs on the mouth-parts of the honey bee into olfactory pores and innervated or tactile hairs, the latter group being divided into spinelike and peglike hairs. Other writers have called the hairs setæ, pegs, cones, bristles, or just "hairs," and the few who have seen the olfactory pores have called them taste-pits, taste-cups, taste-papillæ or beaker-shaped organs, etc. Let us consider the olfactory pores first.

Meinert (1861) seems to be the first to suggest that insects have gustatory organs. He described a row of chitinous canals on the maxillæ and base of the tongue of ants. He thought they were innervated and might serve as gustatory organs. Forel (1873) saw the same or similar structures on the maxillæ and tongue of *Formica,* and he called them gustatory papillæ.

Wolff (1875) first described the olfactory pores on the base of the tongue of the honey bee. He called them taste-beakers in analogy

to the gustatory organs at the base of our tongues, and he thought that the secretion of the salivary glands, always present inside the glossal covering, kept the beakers constantly moist and gustatory stimuli were effected by the saliva changing the honey which passes through the groove in the glossa.

Joseph (1877) saw taste-pits on the bases of the tongues of specimens belonging to nearly all the insect orders, and especially on those of plant-eating insects.

Kraepelin (1883) thought that he found gustatory organs on the proboscides of flies. These were seen on the inner surface of the cushion of the labellum. From his description they may be the same as the olfactory pores under discussion.

Will (1885) described the olfactory pores on the tongue, maxillæ and labial palpi of the honey bee and various other insects in much the same manner as depicted by the present writer. He called them beaker-shaped organs and imagined that they receive gustatory stimuli because the peripheral ends of their nerves come in direct contact with the food. He saw two groups of them on the base of each tongue, and the number of organs in each group varies as follows: *Apis* (worker), about 25; *Osmia,* 14 to 16; *Bombus,* 20 to 24; and Ichneumonidæ, 12 to 14. About 40 organs were seen in each group on the maxillæ of the Apidæ, but very few in the Tenthredinidæ. Will failed to understand the internal anatomy of these organs. He thought the sense cells are multinucleated and that their sense fibers pierce the thin membranes covering the beakers in order to come in contact with the external air.

Breithaupt (1886) describes the pits or pores found on the base of the tongue of the honey bee. Being unable to make thin sections through these organs, he constructed a schematic drawing of a single pore which shows the sense fiber of the spindle-shaped sense cell running to the extremely thin and transparent membrane which covers the pore.

Vom Rath (1886) seems to have found organs similar to the olfactory pores in the labium of millipedes (Chilognatha). Each organ is porelike and is two-thirds filled with a pear-shaped bundle of nerve fibrillæ which pass through the fine pore aperture and come in contact with the external air. The same author (1887, 1888) seems to have seen the same organs on the palpi of beetles.

Janet (1904) found a constant group of olfactory pores on each labial palpus, two rows on the tongue, and some on the pharynx of ants. Those seen by him on the pharynx perhaps really lie on the

cervical plate, as already described by the present writer, because either in sections or in whole mounts of the integuments of the heads it is often difficult to determine whether the pores lie on the pharyngeal plate or on the cervical plate. Janet (1911) saw the same organs widely distributed over the integument of the mandibles of the honey bee. According to him, all the pores, whether on the mouthparts or on the legs, have a similar structure, and they resemble the structure of the olfactory pores described by the present writer; however, there are a few slight differences. He calls the chitinous cone an umbel, which is always separated from the surrounding chitin by a chamber. This chamber communicates with the exterior by means of the pore. The sense fiber, or his manubrium, runs into the umbel, and he thinks that it spreads out over the inner surface of the umbel and does not open into the chamber. Thus the umbel forms a thin layer of chitin which separates the end of the sense fiber from the external air. Janet thinks that the rôle of these organs is evidently to permit the end of the nerve to become distributed on a surface relatively large and separated from the air only by a thin layer of permeable chitin. He imagines that they are special olfactory organs, but different from the olfactory organs on the antennæ. In regard to those on the mandibles, he believes that they aid in building comb and in collecting pollen and propolis.

Hochreuther (1912) found a few olfactory pores on the epicranium near the margin of the eyes, 11 on the first and second joints of the antennæ, a few on the dorsal side of the labrum, very few on the dorsal side of the mandibles, several on the maxillæ and many on the legs of *Dytiscus marginalis*. He called them dome-shaped organs and describes and gives drawings of them in a manner somewhat similar to that of Janet.

We shall now discuss the innervated hairs only briefly, because, as already pointed out, they probably serve neither as olfactory organs nor as gustatory organs.

Wolff (1875) was the first to describe the hairs on the epipharynx. In the honey bee he described each organ as a small cone with a pit in the summit bearing a small hair. He thought that each hair is connected with a sense cell group and that these organs receive olfactory stimuli.

Künkel and Gazagnaire (1881) found innervated hairs on the paraglossæ, on the epipharynx and on the pharyngeal plate of Diptera. They imagined that these hairs receive gustatory stimuli.

Becker (1882) found sense hairs on the ventral side of the labrum of certain Diptera. He believed that they serve as gustatory organs.

Haller (1882) says that the small hairs and pegs on the dorsal side of the labium of *Hydrodroma rubra* probably serve as gustatory organs.

Kraepelin (1882, 1883) attributes a gustatory or olfactory function to certain innervated hairs on the proboscides of Hymenoptera and Diptera.

Kirbach (1883) calls certain small hairs in Lepidoptera gustatory papillæ.

Briant (1884) regards the innervated hairs on the tongue of the bee as merely tactile organs and not as gustatory structures as generally believed.

Sommer (1885) found innervated hairs on the legs, palpi, labrum and labium of *Macrotoma plumbea* (Thysanura), but he says nothing about their function.

Will (1885) gives a drawing of a hair from the tip of the tongue of *Vespa,* but none from *Apis* nor *Bombus.* The sense cell is multinucleated, and the sense fiber stops in the base of the hair, whose walls are thick.

Breithaupt (1886) described papillæ with very short hairs on the mouth-parts of *Bombus.* He thinks that some serve as gustatory organs while others serve as tactile organs, the function being determined by the location of the hairs.

Gazagnaire (1886) says that the gustatory organs in Coleoptera should be found in the buccal cavity in the form of hairs.

Vom Rath (1887, 1888, 1894, 1896) has made a comprehensive study of the morphology of all kinds of hairs on the mouth-parts belonging to various insect orders. All his drawings are good, and each sense hair, peg or cone is usually innervated with a sense cell group, but sometimes with a single sense cell.

Reuter (1888) describes cone-shaped sense hairs on the palpi of Lepidoptera. These are connected with sense cell groups.

Packard (1889, 1903) studied the epipharynx in various insect orders. He almost invariably found hairlike sense organs on each epipharynx examined. These organs are setæ associated with sense pits, cups and rods. Packard seems to think that some of the setæ are used merely to guard the sense cups while the others aid the sense cups in receiving gustatory stimuli.

Nagel (1892, 1894, 1897) has made a special study of the morphology of the olfactory and gustatory organs of insects. He divides

the organs receiving gustatory stimuli into inner gustatory organs and outer ones. The inner ones found inside the buccal cavity are located on the epipharynx as minute pit-pegs or cones. The outer ones are found outside the buccal cavity on the various mouth-parts. They are cones and pit-pegs of various sizes and shapes.

Röhler (1906) found various kinds of sense hairs on the mouth-parts of the grasshopper, *Tryxalis.* He thinks that some of these serve mechanically to examine the food, while the others function as gustatory organs.

The following is a brief discussion of the experimental work pertaining to the sense of taste.

Forel (1873, 1908) was apparently the first to determine experimentally that insects show preferences between foods. When morphine and strychnine are mixed with honey, he says that ants do not at first recognize these substances by smell, but after eating a little honey containing these substances, they immediately leave it. Ants do not always know how to distinguish foods containing injurious substances, because when he fed them honey containing phosphorus, they gorged themselves with it and many of them soon died. In repeating the experiments of Plateau (1885) and Will (1885), Forel amputated the antennæ and the four palpi of several wasps. When he fed them honey containing quinine, they soon left it after eating a little of it, but greedily ate pure honey not containing quinine. From this he concludes that the gustatory faculty is independent of the antennæ and palpi, and that it resides in the mouth. He agrees with Plateau and Will that the amputation of the palpi in no way modifies the olfactory, gustatory or masticatory faculties. He thinks that the palpi serve as special tactile organs.

Will (1885) carried on a series of experiments to demonstrate the sense of taste in insects. He ascertained that wasps, bees, and bumble-bees soon leave foods containing alum, quinine, and salt after eating a little of them. He thinks that the gustatory perception lasts a rather long time, because insects, after eating foods containing these substances, clean their mouths for several minutes and then, when given pure honey, "taste" it several times before definitely beginning to eat. As a general rule, Will found that the larvæ are more "difficult to please" in the choice of their foods than the imago insects.

Lubbock (1899) noticed that some individual ants seem to possess a finer sense of taste than others, and he thinks this is partially explained by the fact that the number of taste-pits is not the same in all individuals. He concludes "that the organs of taste in insects are

certain modified hairs situated either in the mouth itself or on the organs immediately surrounding it." "But though the lower animals undoubtedly possess the sense of taste, it does not, of course, follow that substances taste to them as they do to us. I have found by experiment that sugar and saccharine, which are so similar to us, taste very differently to ants and bees."

In conclusion under this heading, the results obtained by the preceding authors are less satisfactory in explaining that insects have a true gustatory sense than the results obtained by the present author in showing that insects do not have a true gustatory sense, because the preceding authors have found no organs anatomically adapted for receiving gustatory stimuli. Even if the antennæ are amputated, the olfactory organs are not eliminated, because olfactory pores are widely distributed over the integument, and for this reason the olfactory sense cannot be eliminated while testing for the sense of taste. The present writer's opinion is that insects do not have a sense of taste, because their highly developed olfactory organs are sufficiently capable of receiving the odors, however weak, from any and all substances. Whenever the odors are extremely weak, it is then necessary for the insects to eat a little of the foods containing the undesirable substances before being able to smell these substances. For this reason the present writer has called this faculty an olfactory-gustatory sense, although according to the definition of the sense of taste in vertebrates the gustatory perception plays no part in the responses.

GENERAL DISCUSSION

The present writer, and the few other authors who have fed insects foods containing undesirable substances, have observed that the insects sooner or later refuse such foods after eating more or less of them. Judging from this behavior, the other authors have concluded that insects can taste, regardless of knowing whether or not they have sense organs anatomically adapted for receiving gustatory stimuli, and without considering the rôle played by the olfactory sense in these responses. As Parker has already said for vertebrates, and as we well know for ourselves, it is almost impossible to determine whether we taste or smell certain substances when we eat them. To us sometimes a food, before being eaten, emits only a faint odor or no odor at all; but when we eat it, we perceive a pronounced odor. In such a case the odorous particles are not given off until the food is taken into the mouth and mixed with saliva. The same principle is certainly applicable when bees eat candies which contain undesirable

substances emitting extremely weak odors. As quickly as the saliva has dissolved the candy and has had time to effect a chemical or physical change, the odorous particles are given off, and since the olfactory pores on the mouth-parts are nearest the food, they are the first ones to receive the odorous particles. For this reason the so-called gustatory sense in insects is only a phase of the olfactory sense.

That we cannot smell certain substances is no proof that insects cannot smell them, for the many experiments performed by the present writer during the past four years cause him to believe that the olfactory sense in the honey bee is much more highly developed than ours.

It is reasonable to think that many foods and chemicals emit odors, although we may not be able to perceive all of them; but judging from the experiments herein discussed, it is not impossible for bees to discriminate between them better than we can. If they are not able to do this without eating them, only a few "tastes" are necessary to demonstrate their preferences. In a few instances the present writer was not able to discriminate differences between candies containing certain chemicals by using both senses of smell and taste, but the bees were able to distinguish marked differences. It therefore seems evident that this faculty in the honey bee is more highly developed than in man.

In all probability bees have no other means of chemically discriminating between foods than by smelling them, because no sense organs were found connected with the alimentary tract between the pharyngeal plate and the honey stomach, and because the innervated hairs described are not anatomically adapted for this purpose. The walls of the alimentary canal certainly cannot serve such a function except when corrosive or caustic substances are eaten.

After once refusing foods which contain undesirable substances emitting weak odors, bees seem to know these foods and seldom eat any more of them unless forced to partake of them by the removal of the foods they like better.

In conclusion it may be said that the olfactory sense in the honey bee is highly developed and that it serves as an olfactory and gustatory perception combined.

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ABBREVIATIONS

a ....variety *a* of innervated hairs
b_1 to b_4 ....variety *b* of innervated hairs
c_1 to c_{18} ....variety *c* of innervated hairs
d_1 and d_2 ....variety *d* of innervated hairs
e_1 and e_2 ....variety *e* of innervated hairs
f ....variety *f* of innervated hairs
BCav ....buccal cavity
BlSin ....blood sinus
BS ....biting surface of mandible
Can ....canal in rod of glossa
Ch ....chitin
Ch_1 ....flexible chitin
Con ....cone of olfactory pore
Con_1 ....cone of innervated hair on epipharynx
ConT ....connective tissue
CvPl ....cervical plate
E ....esophagus
Ed ....edge of groove on glossa
Ep ....epipharynx
F ....fold in cervical plate
Gls ....glossa, tongue or proboscis
Gv, Gv_1 to Gv_3 ....groove
Hr_1 and Hr_2 .....non-innervated hairs on mandible
Hr^1 to Hr^3 ....pseudo-hairs on glossa
HrCav ....hair cavity
HrMC ....hair-mother cell
HrSk ....hair socket
Hyp ....hypodermis
HypNuc ....hypodermal nucleus
HypS ....hypodermal secretion

K ....keel-shaped lobe of epipharynx
L ....lumen
Lbl ....labellum of glossa
LbPlp ....labial palpus
Lm ....labrum
Lr ....lorum
M_1 to M_{11} ....muscles
Md ....mandible
Mo ....mouth
Mt ....mentum
Mx ....maxilla
MxPlp ....maxillary palpus
N, N_1 to N_6 ......nerves
NB ....nerve branch
Neu ....neurilemma
NF ....nerve fiber
NkFl ....neck of flask-shaped pore
Nt ....notch at base of glossa
Pgl ....paraglossa
Ph ....pharynx
PhPl ....pharyngeal plate
PhPlR ....pharyngeal plate rod
Plg ....palpiger
Por ....olfactory pore
PorAp ....olfactory pore aperture
PorW ....olfactory pore wall
Pr ....chitinous process in base of glossa
R ....rod in glossa
R_1 ....fork of rod in glossa
Rg ....ridge on inner side of mandible
S ....external opening of salivary syringe
SC ....sense cell
SCNuc ....sense cell nucleus
SD ....salivary duct
SF ....sense fiber
SkCav ....cavity in hair socket
SMt ....submentum
SS ....salivary syringe
Tn ....fleshy tongue on ventral surface of mentum
TP ....terminal tip of pharyngeal plate
Tr ....trachea
X ....place on dorsal surface of mentum to which liquid foods perhaps travel before being swallowed

[illegible]